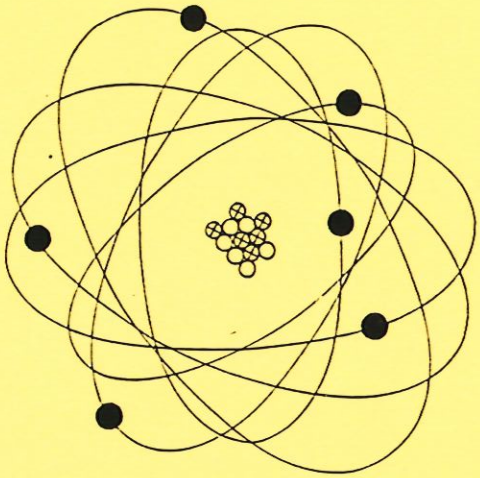
ELECTRICAL SELF-EDUCATION SERIES

BASIC ELECTRICITY I

-FUNDAMENTALS-



Current (I, Amperes) = $\frac{\text{Voltage (E, Volts)}}{\text{Resistance (R, Ohms)}}$	$I = \frac{E}{R}$
$\frac{\text{Voltage (E)}}{\text{Current (I)}}$ = Resistance (R)	$R = \frac{E}{I}$
Current (I) × Resistance (R) = Voltage (E)	$E = IR$

MAINTENANCE & EQUIPMENT TECHNOLOGY
INDIANA HARBOR WORKS-INLAND STEEL CO.

BASIC ELECTRICITY I

-FUNDAMENTALS-

Book 1 of 2

Qui Docet Discit

The only purpose of this publication is for job training, understanding, and instruction. It has been developed to help prepare an employee not only for the particular job which the employee does or will do, but to provide understanding, knowledge, and information of the function and practice in the general area of operational and maintenance techniques the employee is or will be engaged in. Only periodic updating of this publication will be made. Therefore, at anytime, certain additions or deletions which have occurred recently will not be embodied therein until a later review date. This publication, therefore, is neither a workbook nor a manual for measuring job content nor shall it be construed as a documented listing of work requirements.

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MAINTENANCE & EQUIPMENT
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CHAPTER 1

FUNDAMENTAL CONCEPTS OF ELECTRICITY

What is Electricity?

The word "electric" is actually a Greek-derived word meaning AMBER. Amber is a translucent (semitransparent) yellowish mineral, which, in the natural form, is composed of fossilized resin. The ancient Greeks used the words "electric force" in referring to the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the fundamental nature of this force. They could not answer the seemingly simple question, "What is electricity?". This question is still unanswered. Though you might define electricity as "that force which moves electrons," this would be the same as defining an engine as "that force which moves an automobile." You would have described the effect, not the force.

We presently know little more than the ancient Greeks knew about the fundamental nature of electricity, but tremendous strides have been made in harnessing and using it. Elaborate theories concerning the nature and behavior of electricity have been advanced, and have gained wide acceptance because of their apparent truth and demonstrated workability.

From time to time various scientists have found that electricity seems to behave in a constant and predictable manner in given situations, or when subjected to given conditions. These scientists, such as Faraday, Ohm, Lenz, and Kirchhoff, to name only a few, observed and described the predictable characteristics of electricity and electric current in the form of certain rules. These rules are often referred to as "laws." Thus, though electricity itself has never been clearly defined, its predictable nature and easily used form of energy has made it one of the most widely used power sources in modern time. By learning the rules, or laws, applying to the behavior of electricity, and by learning the methods of producing, controlling, and using it, you will have "learned" electricity without ever having determined its fundamental identity.

THE MOLECULE

One of the oldest, and probably the most generally accepted, theories concerning electric current flow is that it is comprised of moving electrons. This is the ELECTRON THEORY. Electrons are extremely tiny parts, or particles, of matter. To study the electron, you must therefore study the structural nature of matter itself. (Anything having mass and inertia, and which occupies any amount of space, is composed of matter.) To study the fundamental structure or composition of any type of matter, it must be reduced to its fundamental fractions. Assume the drop of water in figure 1-1 (A) was halved again and again. By continuing the process long enough, you would eventually obtain the smallest particle of water possible—the molecule. All molecules are composed of atoms.

A molecule of water (H_2O) is composed of one atom of oxygen and two atoms of hydrogen, as represented in figure 1-1 (B). If the molecule of water were further subdivided, there would remain only unrelated atoms of oxygen and hydrogen, and the water would no longer exist as such. This example illustrates the following fact—the molecule is the smallest particle to which a substance can be reduced and still be called by the same name. This applies to all substances—liquids, solids, and gases.

When whole molecules are combined or separated from one another, the change is generally referred to as a PHYSICAL change. In a CHEMICAL change the molecules of the

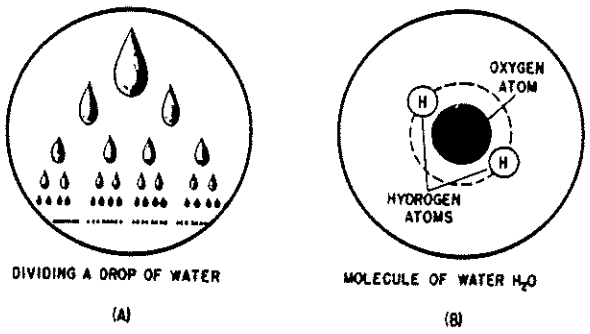


Figure 1-1.—Matter is made up of molecules.

substance are altered such that new molecules result. Most chemical changes involve positive and negative ions and thus are electrical in nature. All matter is said to be essentially electrical in nature.

THE ATOM

In the study of chemistry it soon becomes apparent that the molecule is far from being the ultimate particle into which matter may be subdivided. The salt molecule may be decomposed into radically different substances—sodium and chlorine. These particles that make up molecules can be isolated and studied separately. They are called ATOMS.

The atom is the smallest particle that makes up that type of material called an ELEMENT. The element retains its characteristics when subdivided into atoms. More than 100 elements have been identified. They can be arranged into a table of increasing weight, and can be grouped into families of material having similar properties. This arrangement is called the PERIODIC TABLE OF THE ELEMENTS.

The idea that all matter is composed of atoms dates back more than 2,000 years to the Greeks. Many centuries passed before the study of matter proved that the basic idea of atomic structure was correct. Physicists have explored the interior of the atom and discovered many subdivisions in it. The core of the atom is called the NUCLEUS. Most of the mass of the atom is concentrated in the nucleus. It is comparable to the sun in the solar system, around which the planets revolve. The nucleus contains PROTONS (positively charged particles) and NEUTRONS which are electrically neutral.

Most of the weight of the atom is in the protons and neutrons of the nucleus. Whirling around the nucleus are one or more smaller particles of negative electric charge. THESE ARE THE ELECTRONS. Normally there is one proton for each electron in the entire atom so that the net positive charge of the nucleus is balanced by the net negative charge of the electrons whirling around the nucleus. THUS THE ATOM IS ELECTRICALLY NEUTRAL.

The electrons do not fall into the nucleus even though they are attracted strongly to it. Their motion prevents it, as the planets are prevented from falling into the sun because of their centrifugal force of revolution.

The number of protons, which is usually the same as the number of electrons, determines the kind of element in question. Figure 1-2 shows a simplified picture of several atoms of different materials based on the conception of planetary electrons describing orbits about the nucleus. For example, hydrogen has a nucleus consisting of 1 proton, around which rotates 1 electron. The helium atom has a nucleus containing 2 protons and 2 neutrons with 2 electrons encircling the nucleus. Near the other extreme of the list of elements is curium (not shown in the figure), an element discovered in the 1940's, which has 96 protons and 96 electrons in each atom.

The *Periodic Table of the Elements* is an orderly arrangement of the elements in ascending atomic number (number of planetary electrons) and also in atomic weight (number of protons and neutrons in the nucleus). The various kinds of atoms have distinct masses or

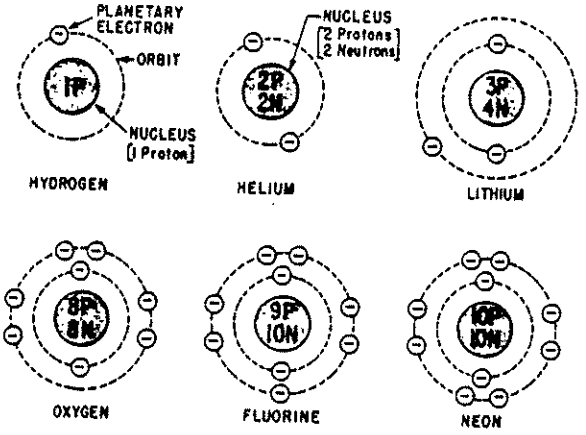


Figure 1-2.—Atomic structure of elements.

weights with respect to each other. The element most closely approaching unity (meaning 1) is hydrogen whose atomic weight is 1.008 as compared with oxygen whose atomic weight is 16. Helium has an atomic weight of approximately 4, lithium 7, fluorine 19, and neon 20, as shown in figure 1-2.

Figure 1-3 is a pictorial summation of the discussion that has just been presented. Visible matter, at the left of the figure, is broken down first to one of its basic molecules, then to one of the molecule's atoms. The atom is then further reduced to its subatomic particles—the protons, neutrons, and electrons. Subatomic particles are electric in nature. That is, they are the particles of matter most affected by an electric force. Whereas the whole molecule or a whole atom is electrically neutral, most subatomic particles are not neutral (with the exception of the neutron). Protons are inherently positive, and electrons are inherently negative. It is these inherent characteristics which make subatomic particles sensitive to electric force.

When an electric force is applied to a conducting medium, such as copper wire, electrons in the outer orbits of the copper atoms are forced out of orbit and impelled along the wire. The direction of electron movement is determined by the direction of the impelling force. The protons do not move, mainly because they are extremely heavy. The proton of the lightest element, hydrogen, is approximately 1,850 times as heavy as an electron. Thus, it is the relatively light electron that is most readily moved by electricity.

When an orbital electron is removed from an atom it is called a FREE ELECTRON. Some of the electrons of certain metallic atoms are so loosely bound to the nucleus that they are comparatively free to move from atom to atom.

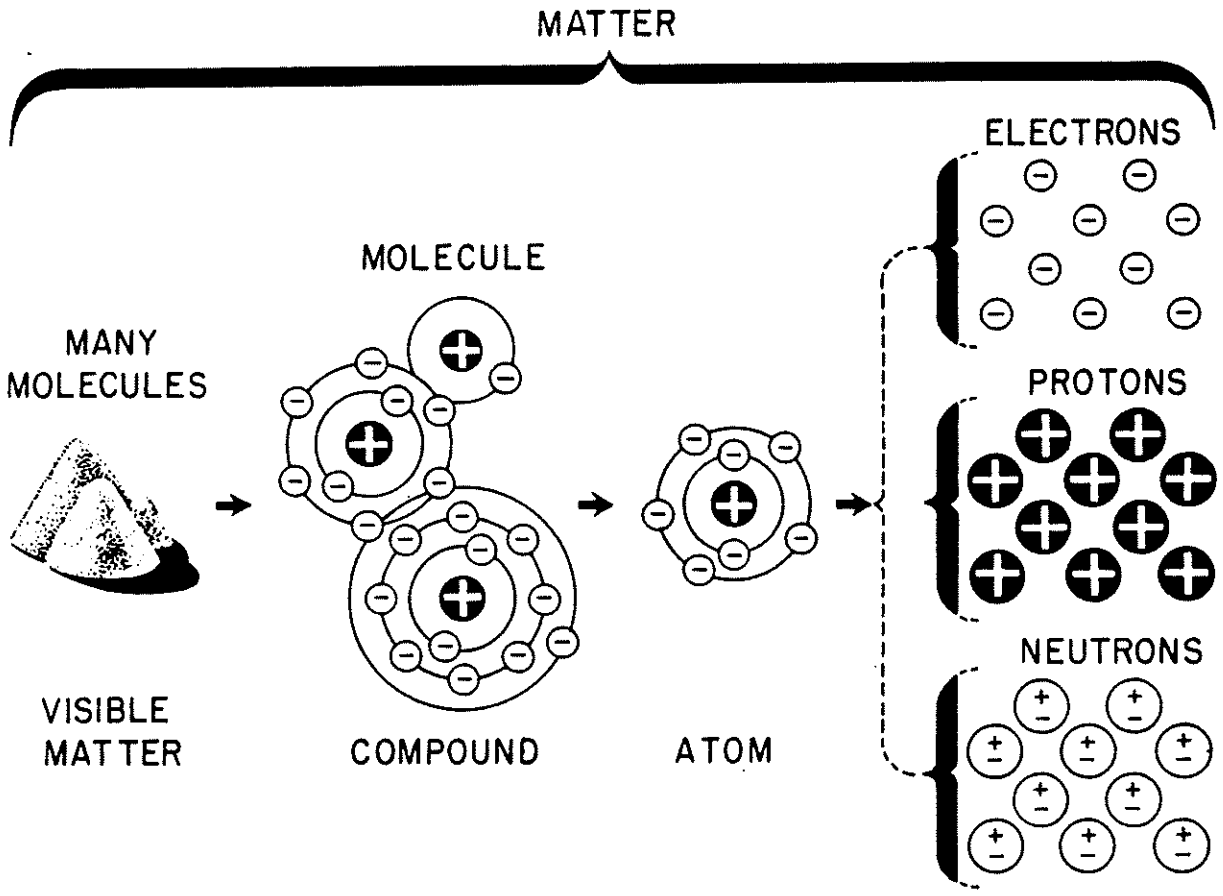


Figure 1-3.—Breakdown of visible matter to electric particles.

Thus, a very small force or amount of energy will cause such electrons to be removed from the atom and become free electrons. It is these free electrons that constitute the flow of an electric current in electrical conductors.

If the internal energy of an atom is raised above its normal state, the atom is said to be EXCITED. Excitation may be produced by causing the atoms to collide with particles that are impelled by an electric force. In this way, energy is transferred from the electric source to the atom. The excess energy absorbed by an atom may become sufficient to cause loosely bound outer electrons to leave the atom against the force that acts to hold them within. An atom that has thus lost or gained one or more electrons is said to be IONIZED. If the atom loses electrons it becomes positively charged and is referred to as a POSITIVE ION. Conversely, if the atom gains electrons, it becomes negatively charged and is referred to as a NEGATIVE ION. Actually then, an ion is a small particle of matter having a positive or negative charge.

Conductors and Insulators

Substances that permit the free motion of a large number of electrons are called CONDUCTORS. Copper wire is considered a good conductor because it has many free electrons. Electrical energy is transferred through conductors by means of the movement of free electrons that migrate from atom to atom inside the conductor. Each electron moves a very short distance to the neighboring atom where it replaces one or more electrons by forcing them out of their orbits. The replaced electrons repeat the process in other nearby atoms until the movement is transmitted throughout the entire length of the conductor. The greater the number of electrons that can be made to move in a material under the application of a given force the better are the conductive qualities of that material. A good conductor is said to have a low opposition or low resistance to the current (electron) flow.

In contrast to good conductors, some substances such as rubber, glass, and dry wood have very few free electrons. In these materials large amounts of energy must be expended in order to break the electrons loose from the influence of the nucleus. Substances containing very few free electrons are called POOR CONDUCTORS, NONCONDUCTORS, or INSULATORS. Actually, there is no sharp dividing line between conductors and insulators, since electron motion is known to exist to some extent in all matter. Electricians simply use the best conductors as wires to carry current and the poorest conductors as insulators to prevent the current from being diverted from the wires.

Listed below are some of the best conductors and best insulators arranged in accordance with their respective abilities to conduct or to resist the flow of electrons.

Conductors	Insulators
Silver	Dry air
Copper	Glass
Aluminum	Mica
Zinc	Rubber
Brass	Asbestos
Iron	Bakelite

Static Electricity

In a natural, or neutral state, each atom in a body of matter will have the proper number of electrons in orbit around it. Consequently, the whole body of matter comprised of the neutral atoms will also be electrically neutral. In this state, it is said to have a "zero charge," and will neither attract nor repel other matter in its vicinity. Electrons will neither leave nor enter the neutrally charged body should it come in contact with other neutral bodies. If, however, any number of electrons are removed from the atoms of a body of matter, there will remain more protons than electrons, and the whole body of matter will become electrically positive. Should the positively charged body come in contact with another body having a

normal charge, or having a negative (too many electrons) charge, an electric current will flow between them. Electrons will leave the more negative body and enter the positive body. This electron flow will continue until both bodies have equal charges.

When two bodies of matter have unequal charges, and are near one another, an electric force is exerted between them because of their unequal charges. However, since they are not in contact, their charges cannot equalize. The existence of such an electric force, where current cannot flow, is referred to as static electricity. "Static" means "not moving." This is also referred to as an ELECTROSTATIC FORCE.

One of the easiest ways to create a static charge is by the friction method. With the friction method, two pieces of matter are rubbed together and electrons are "wiped off" one onto the other. If materials that are good conductors are used, it is quite difficult to obtain a detectable charge on either. The reason for this is that equalizing currents will flow easily in and between the conducting materials. These currents equalize the charges almost as fast as they are created. A static charge is easier to obtain by rubbing a hard nonconducting material against a soft, or fluffy, nonconductor. Electrons are rubbed off one material and onto the other material. This is illustrated in figure 1-4.

When the hard rubber rod is rubbed in the fur, the rod accumulates electrons. Since both fur and rubber are poor conductors, little equalizing current can flow, and an electrostatic charge is built up. When the charge is great enough, equalizing currents will flow in spite of the material's poor conductivity. These currents will cause visible sparks, if viewed in darkness, and will produce a crackling sound.

CHARGED BODIES

One of the fundamental laws of electricity is that LIKE CHARGES REPEL EACH OTHER and UNLIKE CHARGES ATTRACT EACH OTHER. A positive charge and negative charge, being unlike, tend to move toward each other. In the atom the negative electrons are drawn toward the positive protons in the nucleus. This attractive force is balanced by the electron's centrifugal force caused by its rotation about the nucleus. As a result, the electrons remain in orbit and are not drawn into the nucleus. Electrons repel each other because of their like negative charges, and protons repel each other because of their like positive charges.

The law of charged bodies may be demonstrated by a simple experiment. Two pith (paper pulp) balls are suspended near one another by threads, as shown in figure 1-5.

If the hard rubber rod is rubbed to give it a negative charge, and then held against the right-hand ball in part (A), the rod will impart a negative charge to the ball. The right-hand ball will be charged negative with respect to the left-hand ball. When released, the two balls will be drawn together, as shown in figure 1-5 (A). They will touch and remain in contact until the left-hand ball acquires a portion of the negative charge of the right-hand ball, at which time they will swing apart as shown in figure 1-5 (C). If positive charges are placed on both balls (fig. 1-5 (B)), the balls will also be repelled from each other.

COULOMB'S LAW OF CHARGES

The amount of attracting or repelling force which acts between two electrically charged bodies in free space depends on two things—(1) their charges, and (2) the distance between them. The relationship of charge and distance to electrostatic force was first discovered and written by a French scientist named Charles A. Coulomb. Coulomb's Law states that CHARGED BODIES ATTRACT OR REPEL EACH OTHER WITH A FORCE THAT IS DIRECTLY PROPORTIONAL TO THE PRODUCT OF THEIR CHARGES, AND IS INVERSELY PROPORTIONAL TO THE SQUARE OF THE DISTANCE BETWEEN THEM.

ELECTRIC FIELDS

The space between and around charged bodies in which their influence is felt is called an ELECTRIC FIELD OF FORCE. The electric field is always terminated on material objects and extends between positive and negative charges. It can exist in air, glass, paper, or a vacuum. ELECTROSTATIC FIELDS and DIELECTRIC FIELDS are other names used to refer to this region of force.

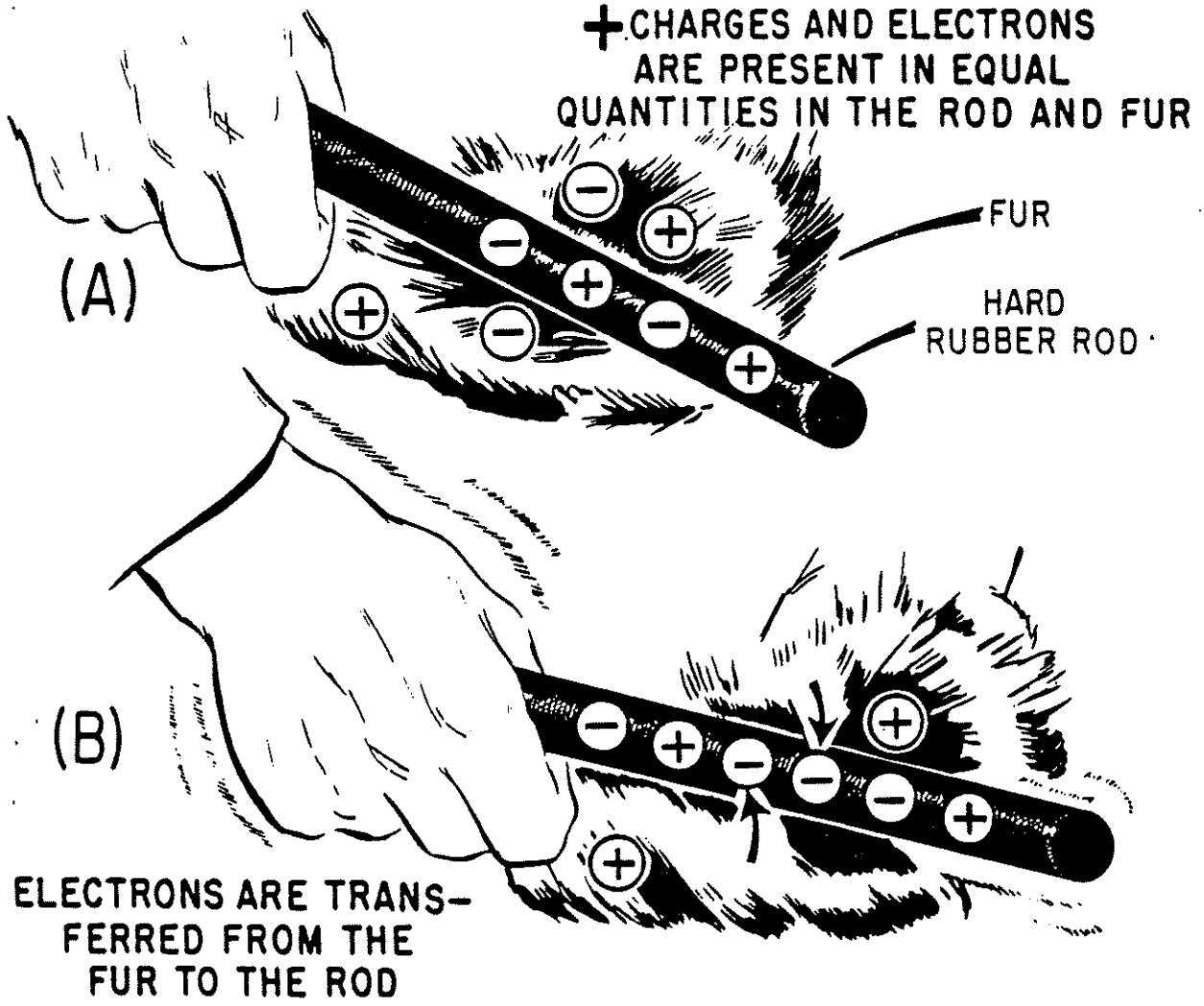

+CHARGES AND ELECTRONS ARE PRESENT IN EQUAL QUANTITIES IN THE ROD AND FUR
FUR
HARD RUBBER ROD
(A)
(B)
ELECTRONS ARE TRANSFERRED FROM THE FUR TO THE ROD

Figure 1-4.—Producing static electricity by friction.

Fields of force spread out in the space surrounding their point of origin and, in general, DIMINISH IN PROPORTION TO THE SQUARE OF THE DISTANCE FROM THEIR SOURCE.

The field about a charged body is generally represented by lines which are referred to as ELECTROSTATIC LINES OF FORCE. These lines are imaginary and are used merely to represent the direction and strength of the field. To avoid confusion, the lines of force exerted by a positive charge are always shown leaving the charge, and for a negative charge they are shown as entering. Figure 1-6 illustrates the use of lines to represent the field about charged bodies.

Figure 1-6 (A) represents the repulsion of like-charged bodies and their associated fields. Part (B) represents the attraction between unlike-charged bodies and their associated fields.

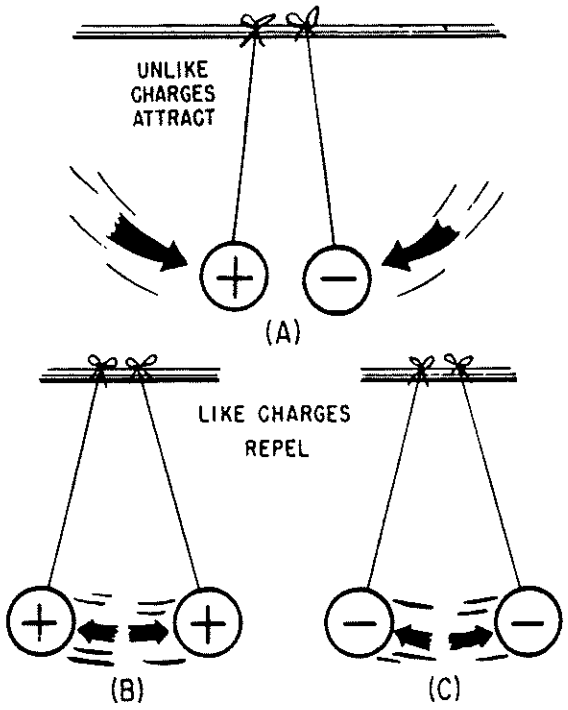


Figure 1-5.—Reaction between charged bodies.

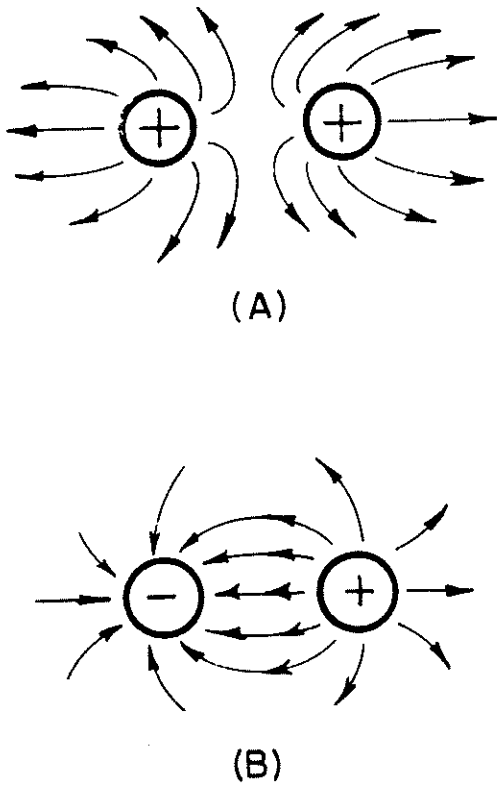


Figure 1-6.—Electrostatic lines of force.

Magnetism

A substance is said to be a magnet if it has the property of magnetism—that is, if it has the power to attract such substances as iron, steel, nickel, or cobalt, which are known as MAGNETIC MATERIALS. A steel knitting needle, magnetized by a method to be described later, exhibits two points of maximum attraction (one at each end) and no attraction at its center. The points of maximum attraction are called MAGNETIC POLES. All magnets have at least two poles. If the needle is suspended by its middle so that it rotates freely in a horizontal plane about its center, the needle comes to rest in an approximately north-south line of direction. The same pole will always point to the north, and the other will always point toward the south. The magnetic pole that points northward is called the NORTH POLE, and the other the SOUTH POLE.

A MAGNETIC FIELD exists around a simple bar magnet. The field consists of imaginary lines along which a MAGNETIC FORCE acts. These lines emanate from the north pole of the magnet, and enter the south pole, returning to the north pole through the magnet itself, thus forming closed loops.

A MAGNETIC CIRCUIT is a complete path through which magnetic lines of force may be established under the influence of a magnetizing force. Most magnetic circuits are composed largely of magnetic materials in order to contain the magnetic flux. These circuits are similar to the ELECTRIC CIRCUIT, which is a complete path through which current is caused to flow under the influence of an electromotive force.

Magnets may be conveniently divided into three groups.

1. NATURAL MAGNETS, found in the natural state in the form of a mineral called magnetite.
2. PERMANENT MAGNETS, bars of hardened steel (or some form of alloy such as alnico) that have been permanently magnetized.

3. ELECTROMAGNETS, composed of soft-iron cores around which are wound coils of insulated wire. When an electric current flows through the coil, the core becomes magnetized. When the current ceases to flow, the core loses most of its magnetism.

Permanent magnets and electromagnets are sometimes called ARTIFICIAL MAGNETS to further distinguish them from natural magnets.

NATURAL MAGNETS

For many centuries it has been known that certain stones (magnetite, Fe_3O_4) have the ability to attract small pieces of iron. Because many of the best of these stones (natural magnets) were found near Magnesia in Asia Minor, the Greeks called the substance MAGNETITE, or MAGNETIC.

Before this, ancient Chinese observed that when similar stones were suspended freely, or floated on a light substance in a container of water, they tended to assume a nearly north-and-south position. Probably Chinese navigators used bits of magnetite floating on wood in a liquid-filled vessel as crude compasses. At that time it was not known that the earth itself acts like a magnet, and these stones were regarded with considerable superstitious awe. Because bits of this substance were used as compasses they were called LOADSTONES (or lodestones), which means "leading stones."

Natural magnets are also found in the United States, Norway, and Sweden. A natural magnet, demonstrating the attractive force at the poles, is shown in figure 1-7 (A).

ARTIFICIAL MAGNETS

Natural magnets no longer have any practical value because more powerful and more conveniently shaped permanent magnets can be produced artificially. Commercial magnets are made from special steels and alloys—for example, alnico, made principally of aluminum, nickel, and cobalt. The name is derived from the first two letters of the three principal elements of which it is composed. An artificial magnet is shown in figure 1-7 (B).

An iron, steel, or alloy bar can be magnetized by inserting the bar into a coil of insulated wire and passing a heavy direct current through the coil, as shown in figure 1-8 (A). This aspect

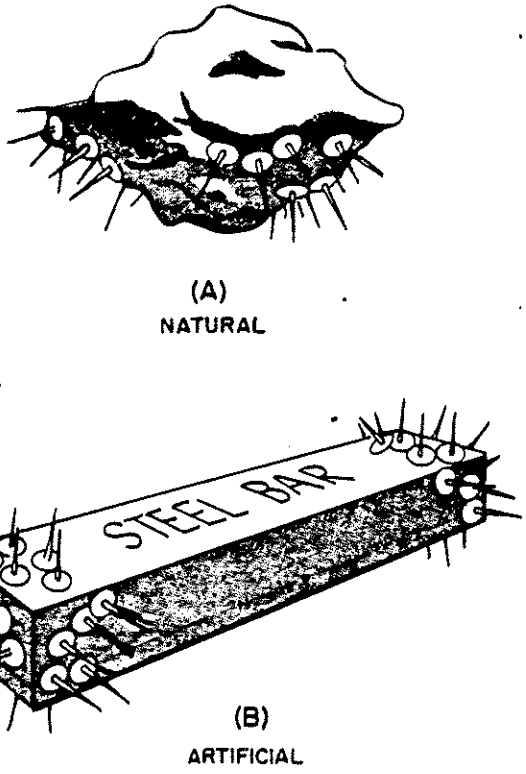


Figure 1-7.—(A) Natural magnet; (B) artificial magnet.

of magnetism is treated later in the chapter. The same bar may also be magnetized if it is stroked with a bar magnet, as shown in figure 1-8 (B). It will then have the same magnetic property that the magnet used to induce the magnetism has—namely, there will be two poles of attraction, one at either end. This process produces a permanent magnet by INDUCTION—that is, the magnetism is induced in the bar by the influence of the stroking magnet.

Artificial magnets may be classified as "permanent" or "temporary" depending on their ability to retain their magnetic strength after the magnetizing force has been removed. Hardened steel and certain alloys are relatively difficult to magnetize and are said to have a LOW PERMEABILITY because the magnetic lines of force do not easily permeate, or distribute themselves readily through the steel. Once magnetized, however, these materials retain a large part of their magnetic strength and are called PERMANENT MAGNETS. Permanent magnets are used extensively in electric instruments, meters, telephone receivers, permanent-magnet loudspeakers, and magnetos. Conversely, substances

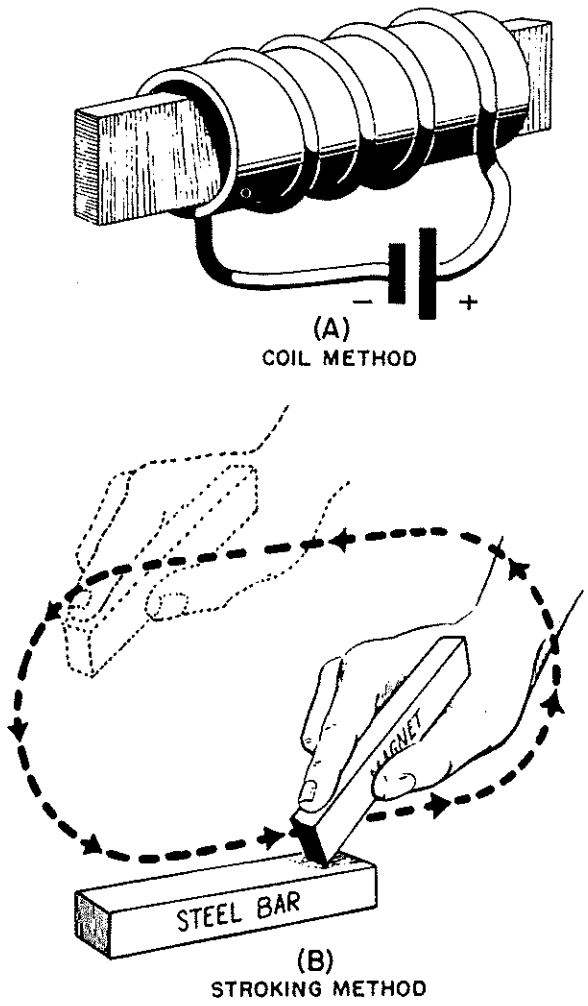


Figure 1-8.—Methods of producing artificial magnets.

that are relatively easy to magnetize—such as soft iron and annealed silicon steel—are said to have a HIGH PERMEABILITY. Such substances retain only a small part of their magnetism after the magnetizing force is removed and are called TEMPORARY MAGNETS. Silicon steel and similar materials are used in transformers where the magnetism is constantly changing and in generators and motors where the strengths of the fields can be readily changed.

The magnetism that remains in a temporary magnet after the magnetizing force is removed is called RESIDUAL MAGNETISM. The fact that temporary magnets retain even a small amount of magnetism is an important factor in the buildup of voltage in self-excited d-c generators.

NATURE OF MAGNETISM

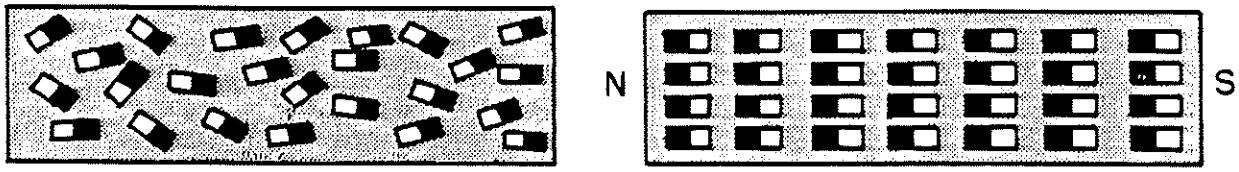
Weber's theory of the nature of magnetism is based on the assumption that each of the molecules of a magnet is itself a tiny magnet. The molecular magnets that compose an unmagnetized bar of iron or steel are arranged at random, as shown by the simplified diagram of figure 1-9 (A). With this arrangement, the magnetism of each of the molecules is neutralized by that of adjacent molecules, and no external magnetic effect is produced. When a magnetizing force is applied to an unmagnetized iron or steel bar, the molecules become alined so that the north poles point one way and the south poles point the other way, as shown in figure 1-9 (B).

If a bar magnet is broken into several parts, as in figure 1-10, each part constitutes a magnet. The north and south poles of these small magnets are in the same respective directions as those of the original magnet. If each of these parts is again broken, the resulting parts are likewise magnets, and the magnetic orientation is the same. If this breaking process could be continued, smaller and smaller pieces would retain their magnetism until each part was reduced to a molecule. It is therefore logical to assume that each of these molecules is a magnet.

A further justification for this assumption results from the fact that when a bar magnet is held out of alinement with the earth's field and is repeatedly jarred, heated, or exposed to a powerful alternating field, the molecular alinement is disarranged and the magnet becomes demagnetized. For example, electric measuring instruments become inaccurate if their permanent magnets lose some of their magnetism because of severe jarring or exposure to opposing magnetic fields.

A theory of magnetism that is perhaps more adequate than the MOLECULAR theory is the DOMAIN theory. Much simplified, this theory may be stated as follows:

In magnetic substances the "atomic" magnets, produced by the movement of the planetary electrons around the nucleus, have a strong tendency to line up together in groups of from 10^{14} to 10^{15} atoms. This occurs without the influence of any external magnetic field. These groups of atoms having their poles orientated in the same direction are called DOMAINS. Therefore, throughout each domain an intense magnetic field is produced. These



UNMAGNETIZED STEEL
(A)

MAGNETIZED STEEL
(B)

Figure 1-9.—Molecular theory of magnetism.

fields are normally in a miscellaneous arrangement so that no external field is apparent when the substance as a whole is unmagnetized. Each tiny domain (10^6 of them may be contained in 1 cubic millimeter) is always magnetized to saturation, and the addition of an external magnetic field does not increase the inherent magnetism of the individual domains.

However, if an external field that is gradually increased in strength is applied to the magnetic substance the domains will line up one by one (or perhaps several at a time) with the external field.

MAGNETIC FIELDS AND LINES OF FORCE

If a bar magnet is dipped into iron filings, many of the filings are attracted to the ends of the magnet, but none are attracted to the center of the magnet. As mentioned previously, the ends of the magnet where the attractive force is the greatest are called the POLES of the magnet. By using a compass, the line of direction of the magnetic force at various points near the magnet may be observed. The compass needle itself is a magnet. The north end of the compass needle always points toward the south pole, S, as shown in figure 1-11 (A), and thus the sense of direction (with respect to the polarity of the bar magnet) is also indicated. At the center, the compass needle points in a direction that is parallel to the bar magnet.

When the compass is placed successively at several points in the vicinity of the bar magnet the compass needle alines itself with the field at each position. The direction of the field is indicated by the arrows and represents the direction in which the north pole of the compass needle will point when the compass is placed in this field. Such a line along which a compass needle alines itself is called a MAGNETIC LINE OF FORCE. As mentioned previously, the magnetic lines of force are assumed to emanate from the north pole of a magnet, pass through the surrounding space, and enter the south pole. The lines of force then pass from the south pole to the north pole inside the magnet to form a closed loop. Each line of force forms an independent closed loop and does not merge with or cross other lines of force. The lines of force between the poles of a horseshoe magnet are shown in figure 1-11 (B).

The space surrounding a magnet, in which the magnetic force acts, is called a MAGNETIC FIELD. Michael Faraday was the first scientist to visualize the magnet field as being in a state of stress and consisting of uniformly distributed lines of force. The entire quantity of magnetic lines surrounding a magnet is called MAGNETIC FLUX. Flux in a magnetic circuit corresponds to current in an electric circuit.

The number of lines of force per unit area is called FLUX DENSITY and is measured in lines per square inch or lines per square centimeter. Flux density is expressed by the equation

$$B = \frac{\Phi}{A},$$

where B is the flux density, Φ (Greek phi) is the total number of lines of flux, and A is the cross-sectional area of the magnetic circuit. If A is in square centimeters, B is in lines per square centimeter, or GAUSS. The terms FLUX and FLOW of magnetism are frequently used in textbooks. However, magnetism itself is not thought to be a stream of particles in motion, but is simply a field of force exerted in space.

A visual representation of the magnetic field around a magnet can be obtained by placing a plate of glass over a magnet and sprinkling iron filings onto the glass. The filings arrange themselves in definite paths between the poles.

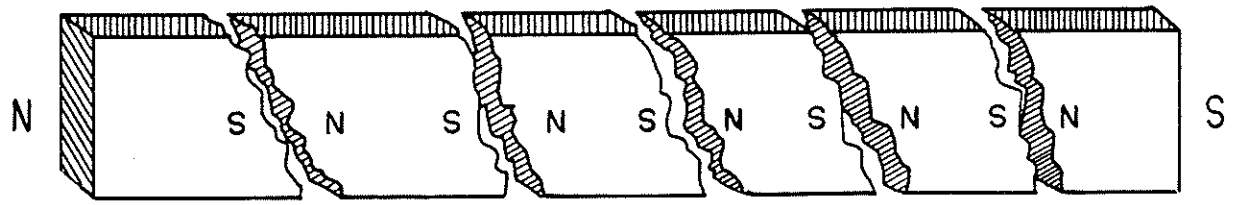
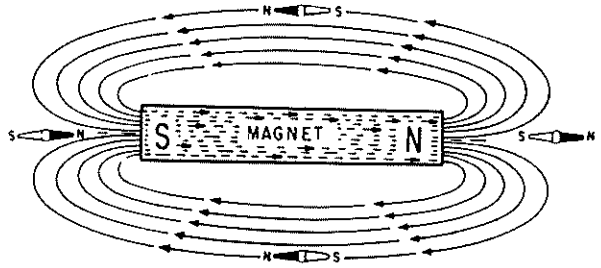
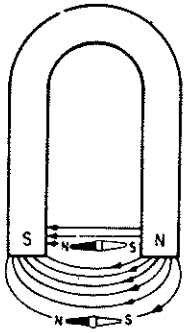


Figure 1-10.—Magnetic poles of a broken magnet.



BAR MAGNET
(A)



HORSESHOE MAGNET
(B)

Figure 1-11.—Magnetic lines of force.

This arrangement of the filings shows the pattern of the magnetic field around the magnet, as in figure 1-12.

The magnetic field surrounding a symmetrically shaped magnet has the following properties:

1. The field is symmetrical unless disturbed by another magnetic substance.
2. The lines of force have direction and are represented as emanating from the north pole and entering the south pole.

LAWS OF ATTRACTION AND REPULSION

If a magnetized needle is suspended near a bar magnet, as in figure 1-13, it will be seen

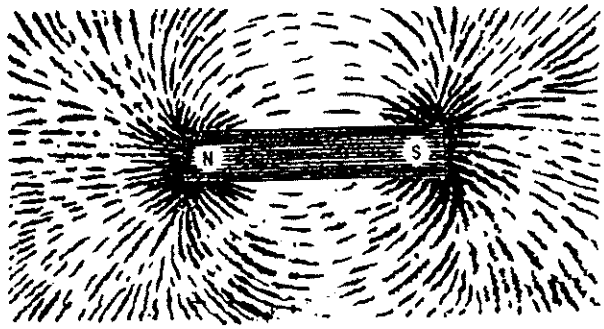


Figure 1-12.—Magnetic field pattern around a magnet.

that a north pole repels a north pole and a south pole repels a south pole. Opposite poles, however, will attract each other. Thus, the first two laws of magnetic attraction and repulsion are:

1. LIKE magnetic poles REPEL each other.
2. UNLIKE magnetic poles ATTRACT each other.

The flux patterns between adjacent UNLIKE poles of bar magnets, as indicated by lines, are shown in figure 1-14 (A). Similar patterns for adjacent LIKE poles are shown in figure 1-14 (B). The lines do not cross at any point and they act as if they repel each other.

Figure 1-15 shows the flux pattern (indicated by lines) around two bar magnets placed close together and parallel with each other. Figure 1-15 (A) shows the flux pattern when opposite poles are adjacent; and figure 1-15 (B) shows the flux pattern when like poles are adjacent.

The THIRD LAW of magnetic attraction and repulsion states in effect that the force of attraction or repulsion existing between two magnetic poles decreases rapidly as the poles are separated from each other. Actually, the force of attraction or repulsion varies directly as the product of the separate pole strengths and inversely as the square of the distance separating the magnetic poles, provided the poles are small enough to be considered as points. For example, if the distance between two north poles is increased from 2 feet to 4 feet, the force of

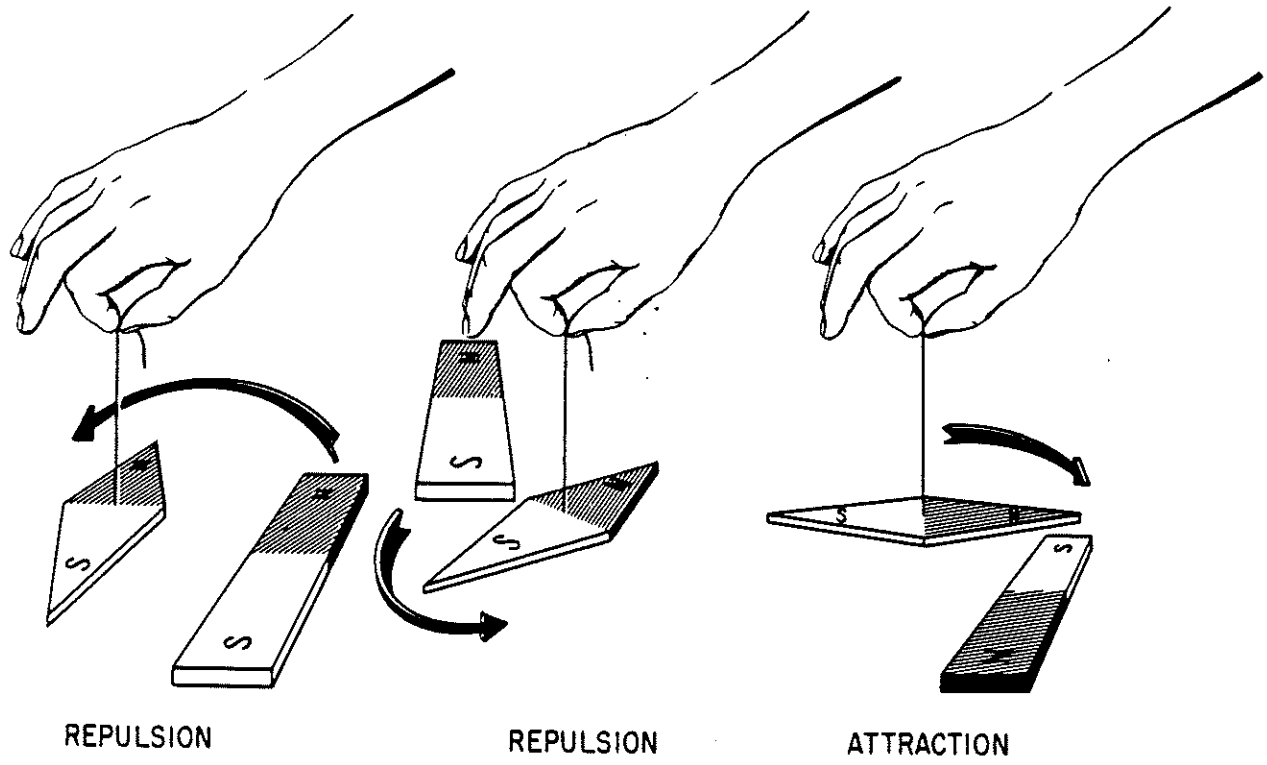


Figure 1-13.—Laws of attraction and repulsion.

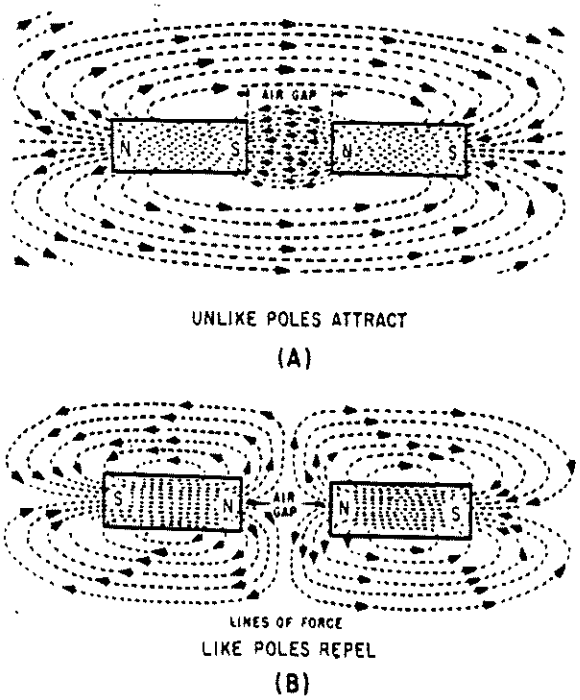


Figure 1-14.—Lines of force between unlike and like poles.

repulsion between them is decreased to one-fourth of its original value. If either pole strength is doubled, the distance remaining the same, the force between the poles will be doubled.

THE EARTH'S MAGNETISM

As has been stated, the earth is a huge magnet; and surrounding the earth is the magnetic field produced by the earth's magnetism. The magnetic polarities of the earth are as indicated in figure 1-16. The geographic poles are also shown at each end of the axis of rotation of the earth. The magnetic axis does not coincide with the geographic axis, and therefore the magnetic and geographic poles are not at the same place on the surface of the earth.

The early users of the compass regarded the end of the compass needle that points in a northerly direction as being a north pole. The other end was regarded as a south pole. On some maps the magnetic pole of the earth towards which the north pole of the compass pointed was designated a north magnetic pole. This magnetic pole was obviously called a north pole because of its proximity to the north geographic pole.

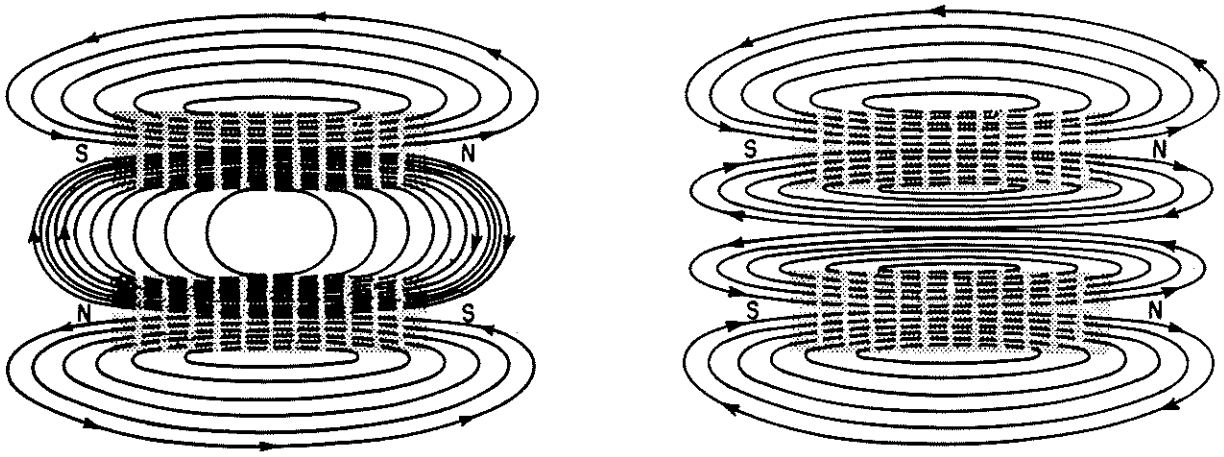


Figure 1-15.–Flux patterns of adjacent parallel bar magnets.

When it was learned that the earth is a magnet and that opposite poles attract, it was necessary to call the magnetic pole located in the northern hemisphere a SOUTH MAGNETIC POLE and the magnetic pole located in the southern hemisphere a NORTH MAGNETIC POLE. The matter of naming the poles was arbitrary. Obviously, the polarity of the compass needle that points toward the north must be opposite to the polarity of the earth's magnetic pole located there.

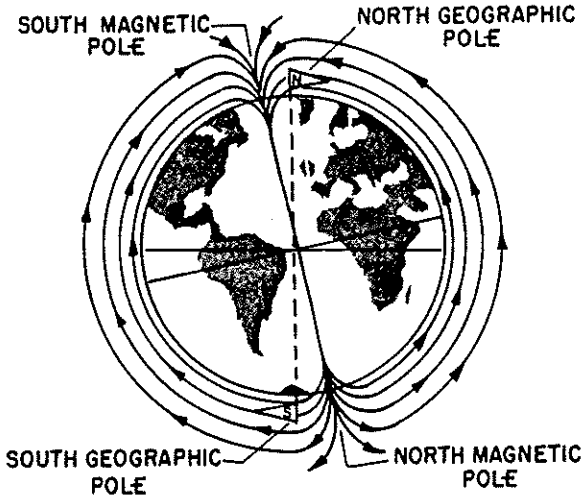


Figure 1-16.–Earth's magnetic poles.

As has been stated, magnetic lines of force are assumed to emanate from the north pole of a magnet and to enter the south pole as closed loops. Because the earth is a magnet, lines of force emanate from its north magnetic pole and enter the south magnetic pole as closed loops. The compass needle alines itself in such a way that the earth's lines of force enter at its south pole and leave at its north pole. Because the north pole of the needle is defined as the end that points in a northerly direction it follows that the magnetic pole in the vicinity of the north geographic pole is in reality a south magnetic pole, and vice versa.

Because the magnetic poles and the geographic poles do not coincide, a compass will not (except at certain positions on the earth) point in a true (geographic) north-south direction—that is, it will not point in a line of direction that passes through the north and south geographic poles, but in a line of direction that makes an angle with it. This angle is called the angle of VARIATION OR DECLINATION.

MAGNETIC SHIELDING

There is not a known INSULATOR for magnetic flux. If a nonmagnetic material is placed in a magnetic field, there is no appreciable change in flux—that is, the flux penetrates the nonmagnetic material. For example, a glass

plate placed between the poles of a horseshoe magnet will have no appreciable effect on the field although glass itself is a good insulator in an electric circuit. If a magnetic material (for example, soft iron) is placed in a magnetic field, the flux may be redirected to take advantage of the greater permeability of the magnetic material as shown in figure 1-17. Permeability is the quality of a substance which determines the ease with which it can be magnetized.

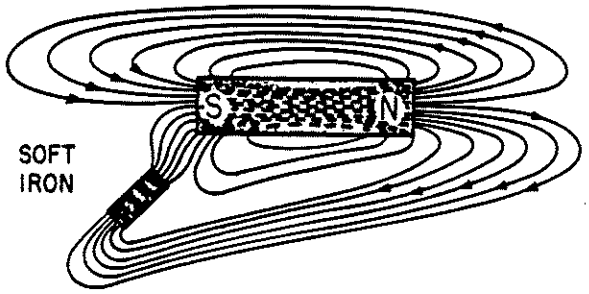


Figure 1-17.—Effects of a magnetic substance in a magnetic field.

The sensitive mechanism of electric instruments and meters can be influenced by stray magnetic fields which will cause errors in their readings. Because instrument mechanisms cannot be insulated against magnetic flux, it is necessary to employ some means of directing the flux around the instrument. This is accomplished by placing a soft-iron case, called a MAGNETIC SCREEN OR SHIELD, about the instrument. Because the flux is established more readily through the iron (even though the path is longer) than through the air inside the case, the instrument is effectively shielded, as shown by the watch and soft-iron shield in figure 1-18.

The study of electricity and magnetism, and how they affect each other, is given more thorough coverage in later chapters of this course.

The discussion of magnetism up to this point has been mainly intended to clarify terms and meanings, such as "polarity," "fields," "lines of force," and so forth. Only one fundamental relationship between magnetism and electricity is discussed in this chapter. This relationship pertains to magnetism as used to generate a voltage and it is discussed under the headings that follows.

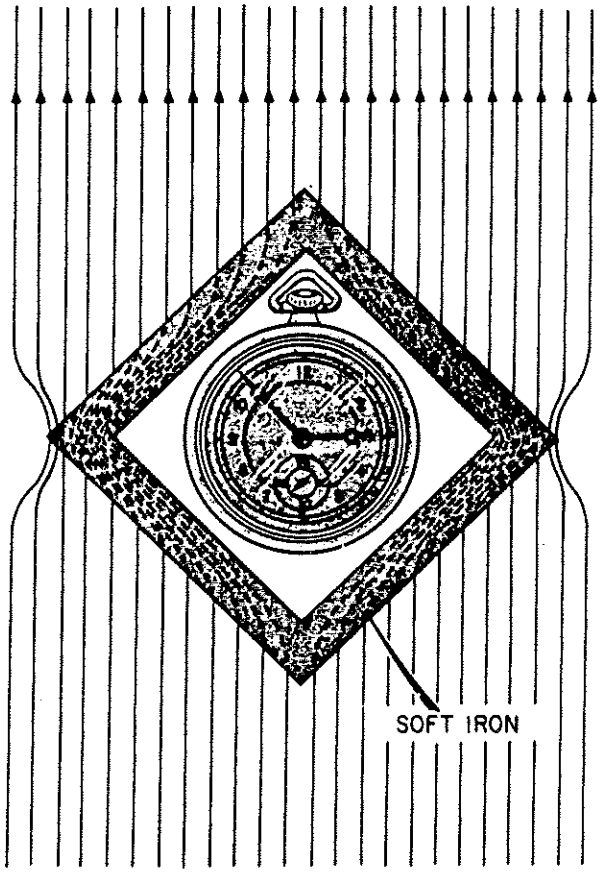


Figure 1-18.—Magnetic shield.

Difference in Potential

The force that causes free electrons to move in a conductor as an electric current is called (1) an electromotive force (e.m.f.), (2) a voltage, or (3) a difference in potential. When a difference in potential exists between two charged bodies that are connected by a conductor, electrons will flow along the conductor. This flow will be from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

An analogy of this action is shown in the two water tanks connected by a pipe and valve in

figure 1-19. At first the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is at maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe, because there is no longer a difference in water pressure between the two tanks.

Current flow through an electric circuit is directly proportional to the difference in potential across the circuit, just as the flow of water through the pipe in figure 1-19 is directly proportional to the difference in water level in the two tanks.

A fundamental law of current electricity is that the CURRENT IS DIRECTLY PROPORTIONAL TO THE APPLIED VOLTAGE.

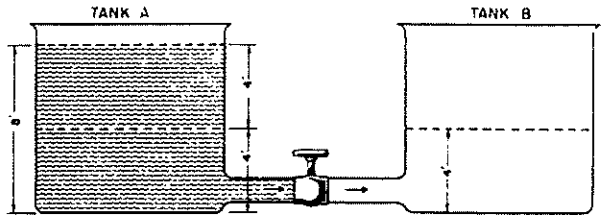


Figure 1-19.—Water analogy of electric difference in potential.

Primary Methods of Producing a Voltage

Presently, there are six commonly used methods of producing a voltage. Some of these methods are much more widely used than others. The methods of utilizing each source will be discussed, and their most common applications will be included. The following is a list of the six most common methods of producing a voltage.

1. FRICTION.—Voltage produced by rubbing two materials together.
2. PRESSURE (Piezoelectricity). — Voltage produced by squeezing crystals of certain substances.
3. HEAT (Thermoelectricity).—Voltage produced by heating the joint (junction) where two unlike metals are joined.
4. LIGHT (Photoelectricity).—Voltage produced by light striking photosensitive (light sensitive) substances.
5. CHEMICAL ACTION.—Voltage produced by chemical reaction in a battery cell.
6. MAGNETISM.—Voltage produced in a conductor when the conductor moves through a magnetic field, or a magnetic field moves through the conductor in such a manner as to cut the magnetic lines of force of the field.

VOLTAGE PRODUCED BY FRICTION

This is the least used of the six methods of producing voltages. Its main application is in Van de Graf generators, used by some laboratories to produce high voltages. As a rule, friction electricity (often referred to as static electricity) is a nuisance. For instance, a flying aircraft accumulates electric charges from the friction between its skin and the passing air. These charges often interfere with radio communication, and under some circumstances can even cause physical damage to the aircraft. You have probably received unpleasant shocks from friction electricity upon sliding across dry seat covers or walking across dry carpets, and then coming in contact with some other object.

VOLTAGE PRODUCED BY PRESSURE

This action is referred to as piezoelectricity. It is produced by compressing or decompressing crystals of certain substances. To study this form of electricity, you must first understand the meaning of the word "crystal." In a crystal, the molecules are arranged in an orderly and uniform manner. A substance in its crystallized state and in its noncrystallized state is shown in figure 1-20.

For the sake of simplicity, assume that the molecules of this particular substance are spherical (ball-shaped). In the noncrystallized state, in part (A), note that the molecules are arranged irregularly. In the crystallized state, part (B), the molecules are arranged in a regular and uniform manner. This illustrates the major physical difference between crystal and noncrystal forms of matter. Natural crystalline matter is rare; an example of matter that is crystalline in its natural form is diamond, which is crystalline carbon. Most crystals are manufactured.

Crystals of certain substances, such as Rochelle salt or quartz, exhibit peculiar electrical characteristics. These characteristics,

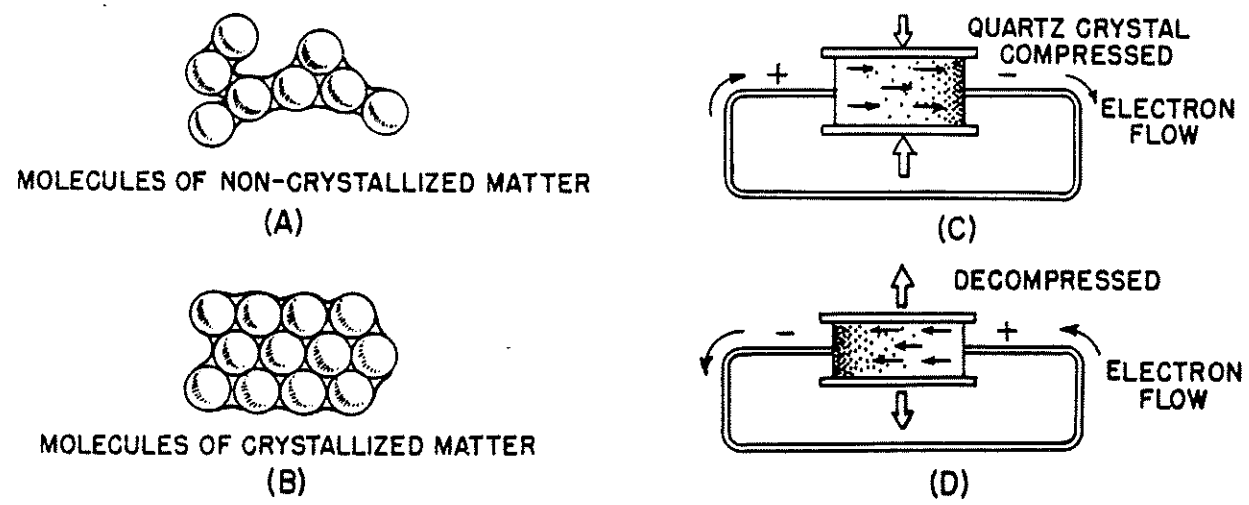


Figure 1-20.—(A) Noncrystallized structure, (B) crystallized structure, (C) compression of a crystal, (D) decompression of a crystal.

or effects, are referred to as "piezoelectric." For instance, when a crystal of quartz is compressed, as in figure 1-20 (C), electrons tend to move through the crystal as shown. This tendency creates an electric difference of potential between the two opposite faces of the crystal. (The fundamental reasons for this action are not known. However, the action is predictable, and therefore useful.) If an external wire is connected while the pressure and e.m.f. are present, electrons will flow. If the pressure is held constant, the electron flow will continue until the charges are equalized. When the force is removed, the crystal is decompressed, and immediately causes an electric force in the opposite direction, as shown in part (D). Thus, the crystal is able to convert mechanical force, either pressure or tension, to electrical force.

The power capacity of a crystal is extremely small. However, they are useful because of their extreme sensitivity to changes of mechanical force or changes in temperature. Due to other characteristics not mentioned here, crystals are most widely used in radio communication equipment. The more complicated study of crystals, as they are used for practical applications, is left for those courses that pertain to the special ratings concerned with them.

VOLTAGE PRODUCED BY HEAT

When a length of metal, such as copper, is heated at one end, electrons tend to move away from the hot end toward the cooler end. This is true of most metals. However, in some metals, such as iron, the opposite takes place and electrons tend to move TOWARD the hot end. These characteristics are illustrated in figure 1-21. The negative charges (electrons) are moving through the copper away from the heat and through the iron toward the heat. They cross from the iron to the copper at the hot junction, and from the copper through the current meter to the iron at the cold junction. This device is generally referred to as a thermocouple.

Thermocouples have somewhat greater power capacities than crystals, but their capacity is still very small if compared to some other sources. The thermoelectric voltage in a thermocouple depends mainly on the difference in temperature between the hot and cold junctions. Consequently, they are widely used to measure temperature, and as heat-sensing devices in automatic temperature control equipment. Thermocouples generally can be subjected to much greater temperatures than ordinary thermometers, such as the mercury or alcohol types.

VOLTAGE PRODUCED BY LIGHT

When light strikes the surface of a substance, it may dislodge electrons from their orbits around the surface atoms of the substance. This occurs because light has energy, the same as any moving force.

Some substances, mostly metallic ones, are far more sensitive to light than others. That is, more electrons will be dislodged and emitted

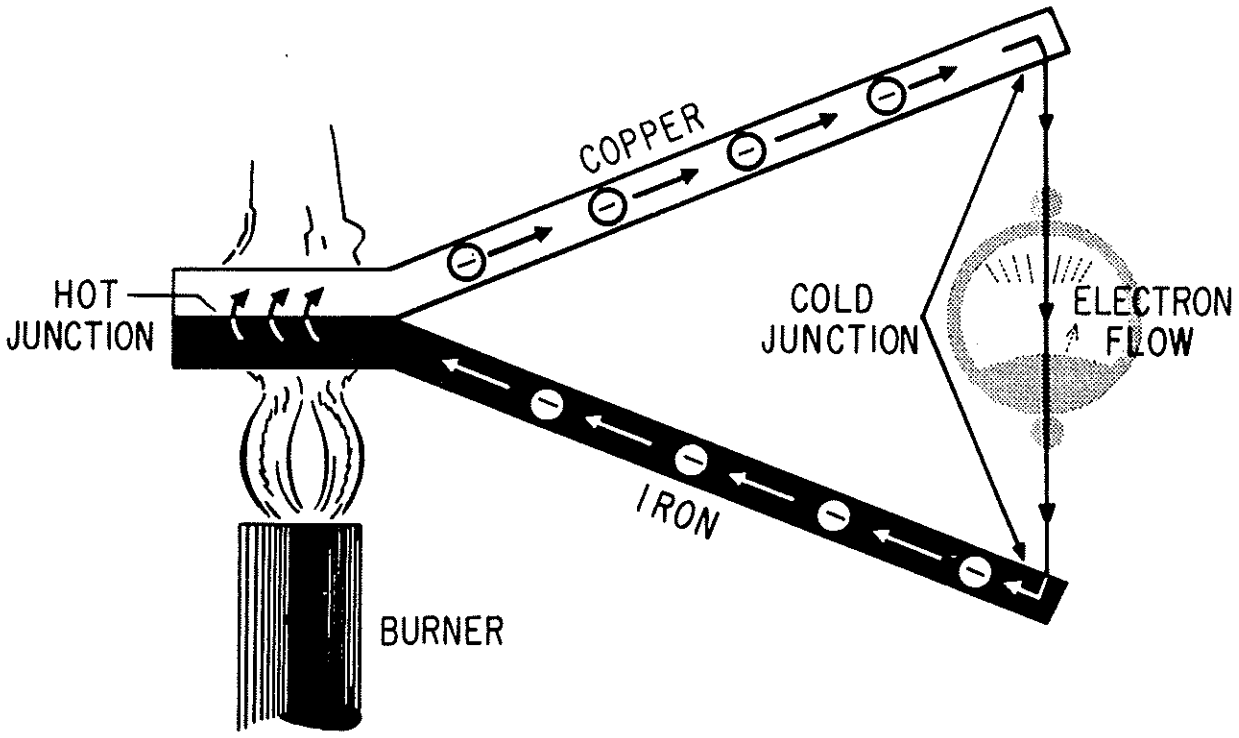


Figure 1-21.—Voltage produced by heat.

from the surface of a highly sensitive metal, with a given amount of light, than will be emitted from a less sensitive substance. Upon losing electrons, the photosensitive (light sensitive) metal becomes positively charged, and an electric force is created. Voltage produced in this manner is referred to as "a photoelectric voltage."

The photosensitive materials most commonly used to produce a photoelectric voltage are various compounds of silver oxide or copper oxide. A complete device which operates on the photoelectric principle is referred to as a "photoelectric cell." There are many sizes and types of photoelectric cells in use, each of which serves the special purpose for which it was designed. Nearly all, however, have some of the basic features of the photoelectric cells shown in figure 1-22.

The cell shown in part (A) has a curved light-sensitive surface focused on the central anode. When light from the direction shown strikes the sensitive surface, it emits electrons toward the anode. The more intense the light, the greater is the number of electrons emitted. When a wire is connected between the filament and the back, or dark side, the accumulated electrons will flow to the dark side. These electrons will eventually

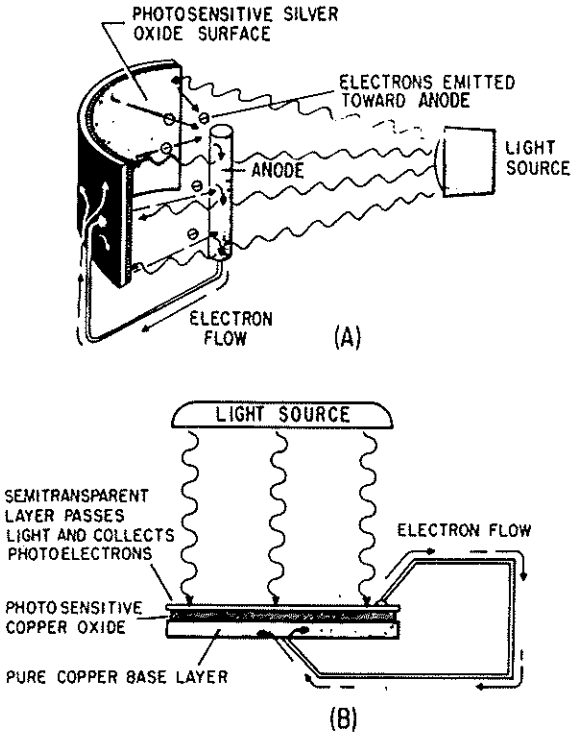


Figure 1-22.—Voltage produced by light.

pass through the metal of the reflector and replace the electrons leaving the light-sensitive surface. Thus, light energy is converted to a flow of electrons, and a usable current is developed.

The cell shown in part (B) is constructed in layers. A base plate of pure copper is coated with light-sensitive copper oxide. An additional layer of metal is put over the copper oxide. This additional layer serves two purposes:

1. It is EXTREMELY thin to permit the penetration of light to the copper oxide.
2. It also accumulates the electrons emitted by the copper oxide.

An externally connected wire completes the electron path, the same as in the reflector type cell. The photocell's voltage is utilized as needed by connecting the external wires to some other device, which amplifies (enlarges) it to a usable level.

A photocell's power capacity is very small. However, it reacts to light-intensity variations in an extremely short time. This characteristic makes the photocell very useful in detecting or accurately controlling a great number of processes or operations. For instance, the photoelectric cell, or some form of the photoelectric principle, is used in television cameras, automatic manufacturing process controls, door openers, burglar alarms, and so forth.

VOLTAGE PRODUCED BY CHEMICAL ACTION

Up to this point, it has been shown that electrons may be removed from their parent atoms and set in motion by energy derived from a source of friction, pressure, heat, or light. In general, these forms of energy do not alter the molecules of the substances being acted upon. That is, molecules are not usually added, taken away, or split-up when subjected to these four forms of energy. Only electrons are involved.

When the molecules of a substance are altered, the action is referred to as CHEMICAL. For instance, if the molecules of a substance combines with atoms of another substance, or gives up atoms of its own, the action is chemical in nature. Such action always changes the chemical name and characteristics of the substance affected. For instance, when atoms of oxygen from the air come in contact with bare iron, they merge with the molecules of iron. This iron is "oxidized." It has changed chemically from iron to iron oxide, or "rust." Its molecules have been altered by chemical action.

In some cases, when atoms are added to or taken away from the molecules of a substance, the chemical change will cause the substance to take on an electric charge. The process of producing a voltage by chemical action is used in batteries and is explained in chapter 2.

VOLTAGE PRODUCED BY MAGNETISM

Magnets or magnetic devices are used for thousands of different jobs. One of the most useful and widely employed applications of magnets is in the production of vast quantities of electric power from mechanical sources. The mechanical power may be provided by a number of different sources, such as gasoline or diesel engines, and water or steam turbines. However, the final conversion of these source energies to electricity is done by generators employing the principle of electromagnetic induction. These generators, of many types and sizes, are discussed in later chapters of this course. The important subject to be discussed here is the fundamental operating principle of ALL such electromagnetic-induction generators.

To begin with, there are three fundamental conditions which must exist before a voltage can be produced by magnetism. You should learn them well, because they will be encountered again and again.

They are:

1. There must be a CONDUCTOR, in which the voltage will be produced.
2. There must be a MAGNETIC FIELD in the conductor's vicinity.
3. There must be relative motion between the field and the conductor. The conductor must be moved so as to cut across the magnetic lines of force, or the field must be moved so that the lines of force are cut by the conductor.

In accordance with these conditions, when a conductor or conductors MOVE ACROSS a magnetic field so as to cut the lines of force, electrons WITHIN THE CONDUCTOR are impelled in one direction or another. Thus, an electric force, or voltage, is created.

In figure 1-23, note the presence of the three conditions needed for creating an induced voltage:

1. A magnetic field exists between the poles of the C-shaped magnet.
2. There is a conductor (copper wire).
3. There is relative motion. The wire is moved back and forth ACROSS the magnetic field.

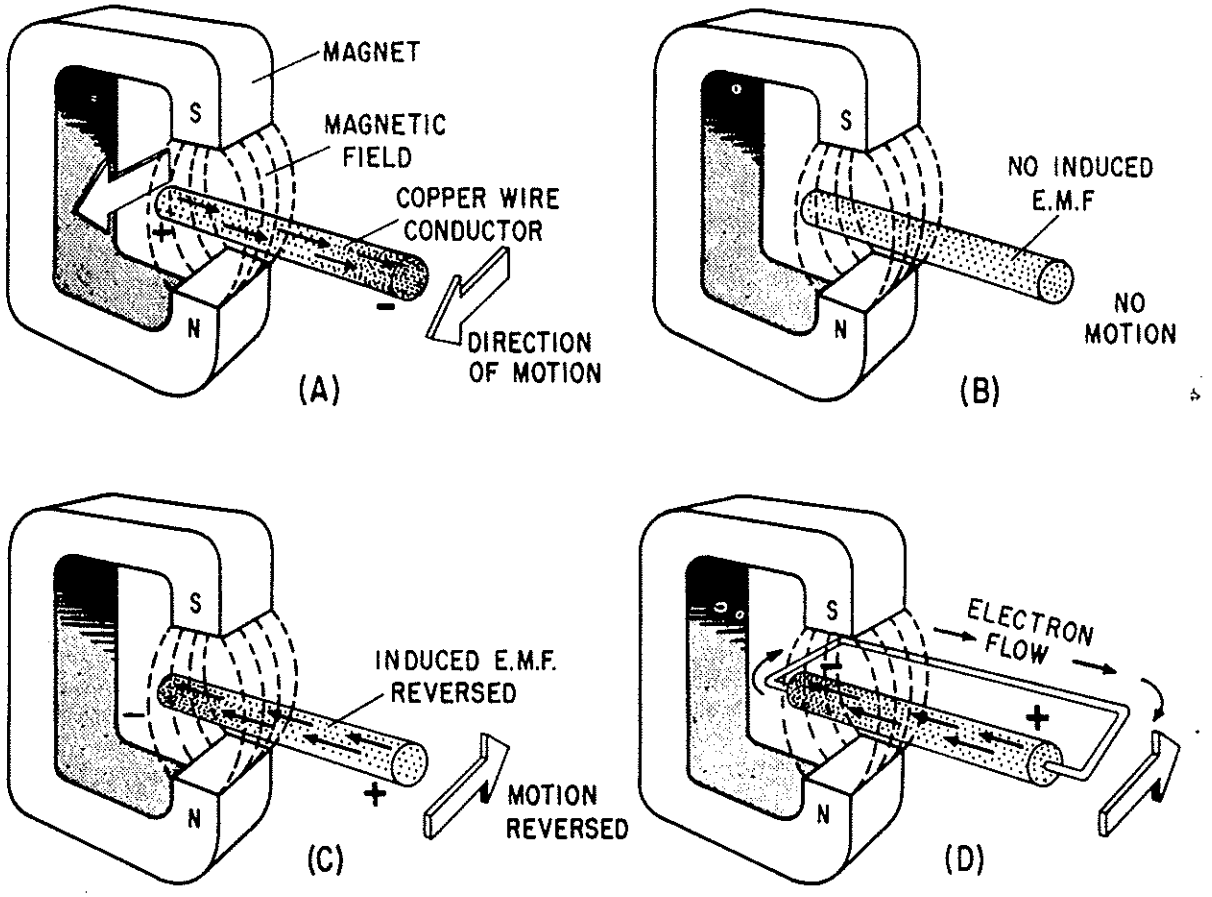


Figure 1-23.—Voltage produced by magnetism.

In part (A) the conductor is moving TOWARD you. This occurs because of the magnetically induced electromotive force (e.m.f.) acting on the electrons in the copper. The right-hand end becomes negative, and the left-hand end positive. In part (B) the conductor is stopped. This eliminates motion, one of the three required conditions, and there is no longer an induced e.m.f. Consequently, there is no longer any difference in potential between the two ends of the wire. In part (C) the conductor is moving AWAY from you. An induced e.m.f. is again created. However, note carefully that the REVERSAL OF MOTION has caused a REVERSAL OF DIRECTION in the induced e.m.f.

If a path for electron flow is provided between the ends of the conductor, electrons will leave the negative end and flow to the positive end. This condition is shown in part (D). Electron flow will continue as long as the e.m.f. exists. In studying figure 1-23, it should be noted that the induced e.m.f. could also have been created by holding the conductor stationary and moving the magnetic field back and forth.

In later chapters of this course, under the heading "Generators," you will study the more complex aspects of power generation by use of mechanical motion and magnetism.

Electric Current

The drift or flow of electrons through a conductor is called ELECTRIC CURRENT. In order to determine the amount (number) of electrons flowing in a given conductor, it is

necessary to adopt a unit of measurement of current flow. The term AMPERE is used to define the unit of measurement of the rate at which current flows (electron flow). The symbol for the ampere is *I*. One ampere may be defined as the flow of 6.28×10^{18} electrons per second past a fixed point in a conductor.

A unit quantity of electricity is moved through an electric circuit when one ampere of current flows for one second of time. This unit is equivalent to 6.28×10^{18} electrons, and is called the COULOMB. The coulomb is to electricity as the gallon is to water. The symbol for the coulomb is *Q*. The rate of flow of current in amperes and the quantity of electricity moved through a circuit are related by the common factor of time. Thus, the quantity of electric charge, in coulombs, moved through a circuit is equal to the product of the current in amperes, *I*, and the duration of flow in seconds, *t*. Expressed as an equation, $Q = It$.

For example, if a current of 2 amperes flows through a circuit for 10 seconds the quantity of electricity moved through the circuit is 2 x 10, or 20 coulombs. Conversely, current flow may be expressed in terms of coulombs and time in seconds. Thus, if 20 coulombs are moved through a circuit in 10 seconds, the average current flow is $\frac{20}{10}$, or 2 amperes. Note that the current flow in amperes implies the rate of flow of coulombs per second without indicating either coulombs or seconds. Thus a current flow of 2 amperes is equivalent to a rate of flow of 2 coulombs per second.

Resistance

Every material offers some resistance, or opposition, to the flow of electric current through it. Good conductors, such as copper, silver, and aluminum, offer very little resistance. Poor conductors, or insulators, such as glass, wood, and paper, offer a high resistance to current flow.

The size and type of material of the wires in an electric circuit are chosen so as to keep the electrical resistance as low as possible. In this way, current can flow easily through the conductors, just as water flows through the pipe between the tanks in figure 1-19. If the water pressure remains constant the flow of water in the pipe will depend on how far the valve is opened. The smaller the opening, the greater the opposition to the flow, and the smaller will be the rate of flow in gallons per second.

In the electric circuit, the larger the diameter of the wires, the lower will be their electrical resistance (opposition) to the flow of current through them. In the water analogy, pipe friction opposes the flow of water between the tanks. This friction is similar to electrical resistance. The resistance of the pipe to the flow of water through it depends upon (1) the length of the pipe, (2) the diameter of the pipe, and (3) the nature of the inside walls (rough or smooth). Similarly, the electrical resistance of the conductors depends upon (1) the length of the wires, (2) the diameter of the wires, and (3) the material of the wires (copper, aluminum, etc.).

Temperature also affects the resistance of electrical conductors to some extent. In most conductors (copper, aluminum, iron, etc.) the resistance increases with temperature. Carbon is an exception. In carbon the resistance decreases as temperature increases. Certain alloys of metals (manganin and constantan) have resistance that does not change appreciably with temperature.

The relative resistance of several conductors of the same length and cross section is given in the following list with silver as a standard of 1 and the remaining metals arranged in an order of ascending resistance:

Silver	1.0
Copper	1.08
Gold	1.4
Aluminum	1.8
Platinum	7.0
Lead	13.5

The resistance in an electrical circuit is expressed by the symbol *R*. Manufactured circuit parts containing definite amounts of resistance are called RESISTORS. Resistance *(R)* is measured in OHMS. One ohm is the resistance of a circuit element, or circuit, that permits a steady current of 1 ampere (1 coulomb per second) to flow when a steady e.m.f. of 1 volt is applied to the circuit.

QUIZ

1. Soft iron is most suitable for use in a
   a. permanent magnet
   b. natural magnet
   c. temporary magnet
   d. magneto
2. Static electricity is most often produced by
   a. pressure
   b. magnetism
   c. heat
   d. friction
3. A fundamental law of electricity is that the current in a circuit is
   a. inversely proportional to the voltage
   b. equal to the voltage
   c. directly proportional to the resistance
   d. directly proportional to the voltage
4. A substance is classed as a magnet if it has
   a. the ability to conduct lines of force
   b. the property of high permeability
   c. the property of magnetism
   d. a high percentage of iron in its composition
5. If a compass is placed at the center of a bar magnet, the compass needle
   a. points to the geographic south pole
   b. points to the geographic north pole
   c. alines itself parallel to the bar
   d. alines itself perpendicular to the bar
6. When electricity is produced by heat in an iron-and-copper thermocouple,
   a. electrons move from north to south
   b. electrons move from the hot junction, through the copper, across the cold junction to the iron, and then to the hot junction
   c. electrons move from the hot junction, through the iron, across the cold junction to the copper, and then return through the copper to the hot junction
   d. none of the above is true
7. The four factors affecting the resistance of a wire are its
   a. length, material, diameter, and temperature
   b. size, length, material, and insulation
   c. length, size, relative resistance, and material
   d. size, insulation, relative resistance, and material
8. Electricity in a battery is produced by
   a. chemical action
   b. chemical reaction
   c. a chemical acting upon metallic plates
   d. all of the above
9. Resistance is always measured in
   a. coulombs
   b. henrys
   c. ohms
   d. megohms
10. The magnetic pole that points northward on a compass
    a. is called the north pole
    b. is actually a south magnetic pole
    c. points to the north magnetic pole of the earth
    d. indicates the direction of the north geographic pole
11. Of the six methods of producing a voltage, which is the least used?
    a. Chemical action
    b. Heat
    c. Friction
    d. Pressure
12. As the temperature of carbon is increased, its resistance will
    a. increase
    b. decrease
    c. remain constant
    d. double
13. Around a magnet, the external lines of force
    a. leave the magnet from the north pole and enter the south pole.
    b. often cross one another
    c. leave the magnet from the south pole and enter the north pole
    d. may be broken by a piece of iron shielding
14. When a voltage is applied to a conductor, free electrons
    a. are forced into the nucleus of their atom
    b. are impelled along the conductor
    c. unite with protons
    d. cease their movement
15. When the molecules of a substance are altered, the action is referred to as
    a. thermal
    b. photoelectric
    c. electrical
    d. chemical
16. When matter is separated into individual atoms, it
    a. has undergone a physical change only
    b. has been reduced to its basic chemicals
    c. retains its original characteristics
    d. has been reduced to its basic elements
17. Most permanent magnets and all electromagnets are
    a. classed as natural magnets
    b. manufactured in various shapes from lodestone
    c. classed as artificial magnets
    d. manufactured in various shapes from magnetite
18. When a conductor moves across a magnetic field
    a. a voltage is induced in the conductor
    b. a current is induced in the conductor
    c. both current and voltage are induced in the conductor
    d. all of the above occurs

19. The nucleus of an atom contains
    a. electrons and neutrons
    b. protons and neutrons
    c. protons and electons
    d. protons, electrons, and neutrons
20. An alnico artificial magnet is composed of
    a. magnetite, steel, and nickle
    b. cobalt, nickle, and varnish
    c. aluminum, copper, and cobalt
    d. aluminum, nickle, and cobalt
21. A material that acts as an insulator for magnetic flux is
    a. glass
    b. aluminum
    c. soft iron
    d. unknown today
22. The force acting through the distance between two dissimilarly-charged bodies
    a. is a chemical force
    b. is referred to as a magnetic field
    c. constitutes a flow of ions
    d. is referred to as an electrostatic field
23. An atom that has lost or gained electrons
    a. is negatively charged
    b. has a positive charge
    c. is said to be ionized
    d. becomes electrically neutral
24. Which of the following is considered to be the best conductor?
    a. Zinc
    b. Copper
    c. Aluminum
    d. Silver
25. As the temperature increases, the resistance of most conductors also increases. A conductor that is an exception to this is
    a. aluminum
    b. carbon
    c. copper
    d. brass

CHAPTER 2

BATTERIES

Storage batteries are widely used as sources of d-c voltage in automobiles, boats, aircraft, ships, telephone systems, and in portable lighting equipment. In most cases, they are used as standby power supplies. In others, batteries are the only source of power.

A battery consists of a number of CELLS assembled in a common container and connected to each other.

Common Battery Terms

THE CELL

A cell is a device that transforms chemical energy into electrical energy. The simplest cell, known as either a galvanic or voltaic cell, is shown in figure 2-1. It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a solution of water (H_2O) and sulfuric acid (H_2SO_4).

The cell is the fundamental unit of the battery. A simple cell consists of two strips, or electrodes, placed in a container that also holds the electrolyte. The electrolyte in a battery may be in the form of either a liquid or a paste.

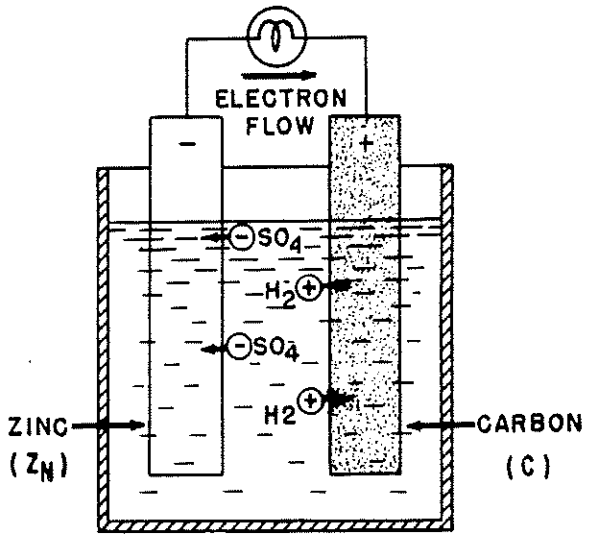


Figure 2-1.—Simple voltaic cell.

ELECTRODES

The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell, they are carbon and zinc strips that are placed in the electrolyte; while in the dry cell (fig. 2-2), they are the carbon rod in the center and the zinc container in which the cell is assembled.

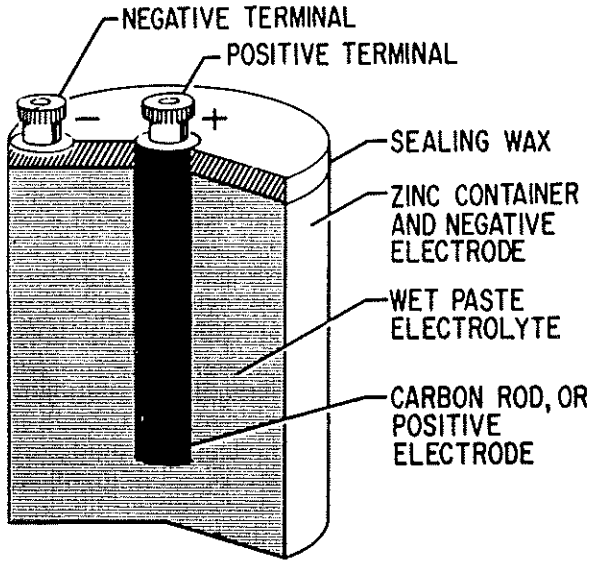


Figure 2-2.—Dry cell, cross-sectional view.

ELECTROLYTE

The electrolyte is the solution that acts upon the electrodes which are placed in it. The

electrolyte may be a salt, an acid, or an alkaline solution. In the simple galvanic cell and in the automobile storage battery, the electrolyte is in a liquid form; while in the dry cell, the electrolyte is a paste.

PRIMARY CELL

A primary cell is one in which the chemical action eats away one of the electrodes, usually the negative. When this happens, the electrode must be replaced or the cell must be thrown away. In the galvanic type cell the zinc electrode and the liquid solution are usually replaced when this happens. In the case of the dry cell, it is usually cheaper to buy a new cell. The simple voltaic cell is a primary cell.

SECONDARY CELL

A secondary cell is one in which the electrodes and the electrolyte are altered by the chemical action that takes place when the cell delivers current. These cells may be restored to their original condition by forcing an electric current through them in the opposite direction to that of discharge. The automobile storage battery is a common example of the secondary cell.

THE BATTERY

The battery consists of two or more cells placed in a common box or container. The cells are connected to each other in series, in parallel, or in some combination of series and parallel, depending upon the amount of voltage and current required of the battery. For example, a 45-volt B battery used for radio work may consist of 30 cells of 1-1/2 volts each, connected in series. The 12-volt battery used in the automobile of today consists of 6 cells of 2 volts each, connected in series.

Battery Chemistry

ACTION ON DISCHARGE

If a conductor is connected externally to the electrodes of a cell, electrons will flow under the influence of a difference in potential across the electrodes from the zinc (negative) through the external conductor to the carbon (positive) returning within the solution to the zinc. After a short period of time, the zinc will begin to waste away because of the "burning" action of the acid. If zinc is surrounded by oxygen, it will burn(become oxidized) as a fuel. In this respect, the cell is like a chemical furnace in which energy released by the zinc is transformed into electrical energy rather than heat energy.

The voltage across the electrodes depends upon the materials comprising them and the composition of the solution. The difference of potential between carbon and zinc electrodes in a dilute solution of sulfuric acid and water is about 1.5 volts. In most practical primary cells the voltage does not exceed 2 volts.

The current that a primary cell may deliver depends upon the resistance of the entire curcuit, including that of the cell itself. The internal resistance of the primary cell depends upon the size of the electrodes, the distance between them in the solution, and the resistance of the solution. The larger the electrodes and the closer together they are in solution (without touching), the lower will be the internal resistance of the primary cell and the more current it will be capable of supplying to a load.

When current flows through a cell, the zinc will gradually be dissolved in solution and the acid will be neutralized. A chemical equation is sometimes used to show the chemical action that takes place. The symbols in the equation represent the different materials that are used. The symbol for carbon is C and for zinc Zn. The equation is quantitative and equates the number of parts of the materials used before and after the zinc is oxidized. It will be remembered from chapter 1 that all matter is composed of atoms and molecules, with the atom being the smallest part of an element and the molecule the smallest part of a compound.

A COMPOUND is a chemical combination of two or more elements in which the physical properties of the compound are different from those of the elements comprising it. For instance, a molecule of water, H_2O, is composed of two atoms of hydrogen, H_2, and one atom of oxygen, O. Ordinarily, hydrogen and oxygen are gases, but when combined, as stated above, they form water, which normally is a liquid. On the other hand, sulfuric acid, H_2SO_4, and water,

H_2O form a MIXTURE (not a compound), because the identity of both liquids is preserved when they are in solution together.

When a current flows through a primary cell having carbon and zinc electrodes and a dilute solution of sulfuric acid and water, the chemical reaction that takes place can be expressed as:

$$Zn + H_2SO_4 + H_2O \xrightarrow[\text{discharge}]{} ZnSO_4 + H_2O + H_2\uparrow.$$

The expression indicates that as current flows, a molecule of zinc combines with a molecule of sulfuric acid to form a molecule of zinc sulfate ($ZnSO_4$) and a molecule of hydrogen (H_2). The zinc sulfate dissolves in solution and the hydrogen appears as gas bubbles around the carbon electrode. As current continues to flow, the zinc is gradually consumed and the solution changes to zinc sulfate and water. The carbon electrode does not enter into the chemical changes taking place but simply provides a return path for the current.

In the process of oxidizing the zinc, the solution breaks up into positive and negative ions that move in opposite directions through the solution (fig. 2-1). The positive ions are hydrogen ions that appear around the carbon electrode (positive terminal). They are attracted to it by the free electrons from the zinc that are returning to the cell by way of the external load and the positive carbon terminal. The negative ions are SO_4 ions that appear around the zinc electrode. Positive zinc ions enter the solution around the zinc electrode and combine with the negative SO_4 ions to form zinc sulfate, $ZnSO_4$, a grayish-white substance that dissolves in water. At the same time that the positive and negative ions are moving in opposite directions in the solution, electrons are moving through the external circuit from the negative zinc terminal, through the load, and back to the positive carbon terminal. When the zinc is used up, the voltage of the cell is reduced to zero. There is no appreciable difference in potential between zinc sulfate and carbon in a solution of zinc sulfate and water.

POLARIZATION

The chemical action that takes place in the cell (fig. 2-1) while the current is flowing causes hydrogen bubbles to form on the surface of the positive carbon electrode in great numbers until the entire surface is surrounded. This action is called POLARIZATION. Some of these bubbles rise to the surface of the solution and escape into the air. However, many of the bubbles remain until there is no room for any more to be formed.

The hydrogen tends to set up an electromotive force in the opposite direction to that of the cell, thus increasing the effective internal resistance, reducing the output current, and lowering the terminal voltage.

A cell that is heavily polarized has no useful output. There are several ways to prevent polarization from occurring or to overcome it after it has occurred. The very simplest method might be to remove the carbon electrode and wipe off the hydrogen bubbles. When the electrode is replaced in the electrolyte, the e.m.f. and current are again normal. This method is not practicable because polarization occurs rapidly and continuously in the simple voltaic cell. A commercial form of voltaic cell, known as the DRY CELL, employs a substance rich in oxygen as a part of the positive carbon electrode, which will combine chemically with the hydrogen to form water, H_2O. One of the best depolarizing agents used is manganese dioxide (MnO_2), which supplies enough free oxygen to combine with all of the hydrogen so that the cell is practically free from polarization.

The chemical action that occurs may be expressed as

$$2MnO_2 + H_2 \longrightarrow Mn_2O_3 + H_2O.$$

The manganese dioxide combines with the hydrogen to form water and a lower oxide of manganese. Thus the counter e.m.f. of polarization does not exist in the cell, and the terminal voltage and output current are maintained normal.

LOCAL ACTION

When the external circuit is opened, the current will cease to flow, and theoretically all chemical action within the cell will stop. However, commercial zinc contains many impurities, such as iron, carbon, lead, and arsenic. These impurities form many small cells within the zinc electrode in which current flows between the zinc and its impurities. Thus the zinc is oxidized even though the cell itself is an open circuit. This wasting away of the zinc on open circuit is called LOCAL ACTION. For example, a small local cell exists on a zinc plate containing impurities of iron, as shown in figure 2-3. Electrons flow between the zinc and iron and the solution around the impurity becomes ionized. The negative SO_4 ions combine with the positive

Zn ions to form $ZnSO_4$. Thus the acid is depleted in solution and the zinc consumed.

Local action may be prevented by using pure zinc (which is not practical), by coating the zinc with mercury, or by adding a small percentage of mercury to the zinc during the manufacturing process. The treatment of the zinc with mercury is called AMALGAMATING the zinc. Since mercury is 13.6 times as heavy as an equal volume of water, small particles of impurities having a lower relative weight than that of mercury will rise (float) to the surface of the mercury. The removal of these impurities from the zinc prevents local action. The mercury is not readily acted upon by the acid, and even when the cell is delivering current to a load, the mercury continues to act on the impurities in the zinc, causing them to leave the surface of the zinc electrode and float to the surface of the mercury. This process greatly increases the life of the primary cell.

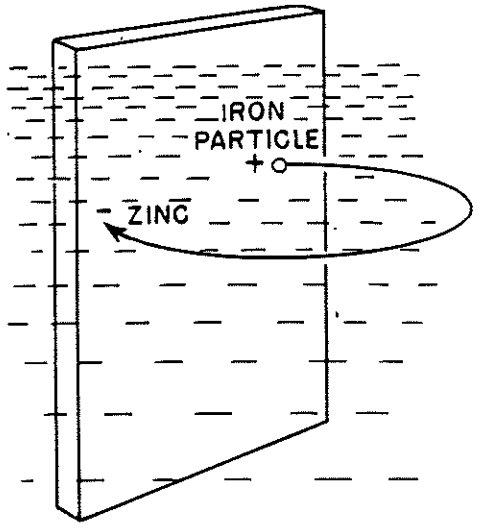


Figure 2-3.—Local action on zinc electrode.

Types of Batteries

THE DRY (PRIMARY) CELL

The dry cell is so called because its electrolyte is not in a liquid state. Actually, the electrolyte is a moist paste. If it should become dry, it would no longer be able to transform chemical energy to electrical energy. The name DRY CELL, therefore, is not strictly correct in a technical sense.

Construction of the Dry Cell

The construction of a common type of dry cell is shown in figure 2-4. The internal parts of the cell are located in a cylindrical zinc container. This zinc container serves as the cell's negative electrode. The container is lined with a nonconducting material, such as blotting paper, to insulate the zinc from the paste. A carbon electrode is located in the center, and it serves as the positive terminal of the cell. The paste is a mixture of several substances. Its composition may vary, depending on its manufacturer. Generally, however, the paste will contain some combination of the following substances: ammonium chloride (sal ammoniac), powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite, and water.

This paste, which is packed in the space between the carbon and the blotting paper, also serves to hold the carbon electrode rigid in the center of the cell. When packing the paste in the cell, a small expansion space is left at the top. The cell is then sealed with asphalt-saturated cardboard.

Binding posts are attached to the electrodes so that wires may be conveniently connected to the cell.

Since the zinc container is one of the electrodes, it must be protected with some insulating material. Therefore, it is common practice for the manufacturer to enclose the cells in cardboard containers.

Chemical Action of the Dry Cell

The dry cell (fig. 2-4) is fundamentally the same as the simple voltaic cell (wet cell) described earlier, as far as its internal chemical action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes, produces the voltage of the cell. The manganese dioxide is added to reduce the polarization when line current flows, and the zinc chloride reduces local action when the cell is idle. The blotting paper serves two purposes, one being to keep the paste

from making actual contact with the zinc container and the other being to permit the electrolyte to filter through to the zinc slowly. The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

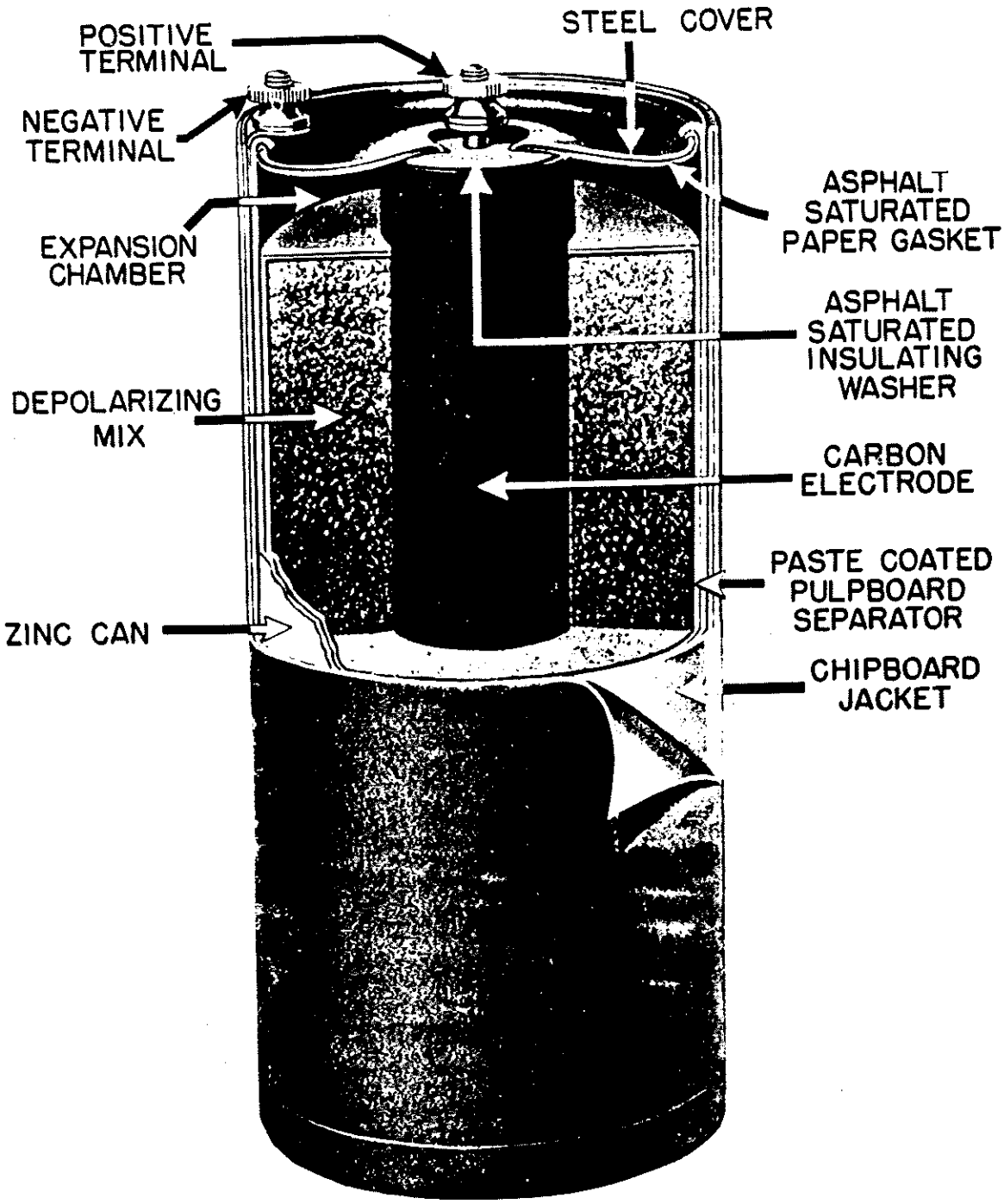


Figure 2-4.—Cutaway view of the general-purpose dry cell.

Rating of the Standard Size Cell

One of the most popular sizes in general use is the standard, or No. 6, dry cell. It is approximately 2-1/2 inches in diameter and 6 inches in length. The voltage is about 1-1/2 volts when new but decreases as the cell ages. When the open-circuit voltage falls below 0.75 to 1.2 volts (depending upon the circuit requirements), the cell is usually discarded. The amount of current that the cell can deliver, and still give satisfactory service, depends upon the length of time that the current flows. For instance, if a No. 6 cell is to be used in a portable radio, it is likely to supply current constantly for several hours. Under these conditions, the current should not exceed 1/8 ampere, the rated constant-current capacity of a No. 6 cell. If the same cell is required to supply current only occasionally, for only short periods of time, it could supply currents of several amperes without undue injury to the cell. As the time duration of each discharge decreases, and the interval of time between discharges increases the allowable amount of current available for each discharge becomes higher, up to the amount that the cell will deliver on short circuit.

The short-circuit current test is another means of evaluating the condition of a dry cell. A new cell, when short circuited through an ammeter, should supply not less than 25 amperes. A cell that has been in service should supply at least 10 amperes if it is to remain in service.

Rating of the Unit Size Cell

Another popular size of dry cell is the size D, which is 1-3/8 inches in diameter and 2-3/4 inches in length. This cell is also known as the unit cell. Its most common use is in standard-sized flashlights and in test instruments. The size D cell voltage is 1.5 volts when new. The short-circuit current test of a new cell should be from 5 to 6 amperes. The corrosion and swelling of discharged cells may ruin flashlights, instruments, or whatever device uses them. To prevent this action, some manufacturers place a steel jacket around the zinc container.

Shelf Life

A cell that is not put into use (sits on the shelf) will gradually deteriorate because of slow internal chemical actions (local action) and changes in moisture content. However, this deterioration is usually very slow if cells are properly stored. High-grade cells of the larger sizes, such as the standard No. 6, should have a shelf life of a year or more. Smaller size cells have a proportionately shorter shelf life, ranging down to a few months for the very small sizes. If unused cells are stored in a cool place, their shelf life will be greatly increased.

Mercury Cells

A fairly recent addition to the types of batteries used in the Navy is the mercury cell. It is known also as the "Ruben" or "RM" cell. Presently, its uses are limited mainly to precision measuring instruments and guided missiles. The mercury cell's most desirable characteristics are (1) a high power-output-to-weight ratio, (2) an almost flat discharge-voltage curve, and (3) a relatively long shelf life under conditions of high temperature and humidity. Mercury cells presently in use, such as the RM-1R and RM-4R, are very small compared to most lead-acid cells. However, larger mercury cells are presently in the developmental stage. The approximate size of two typical mercury cells is shown in figure 2-5 (A).

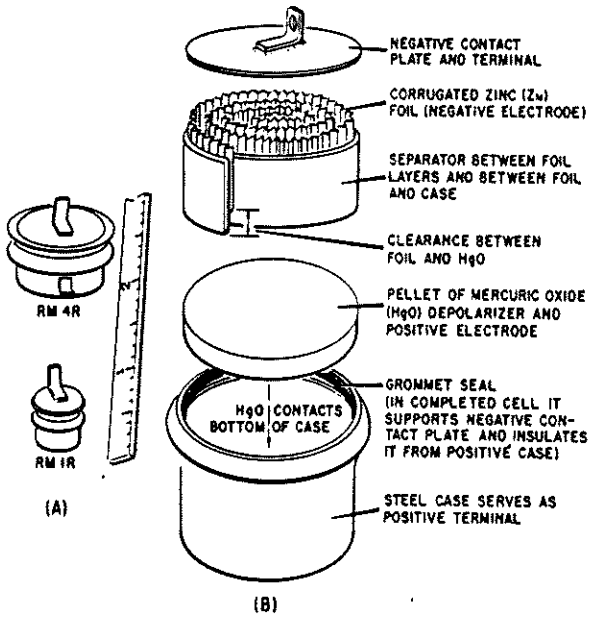

RM 4R
RM 1R
(A)
NEGATIVE CONTACT PLATE AND TERMINAL
CORRUGATED ZINC (Zn) FOIL (NEGATIVE ELECTRODE)
SEPARATOR BETWEEN FOIL LAYERS AND BETWEEN FOIL AND CASE
CLEARANCE BETWEEN FOIL AND HgO
PELLET OF MERCURIC OXIDE (HgO) DEPOLARIZER AND POSITIVE ELECTRODE
GROMMET SEAL (IN COMPLETED CELL IT SUPPORTS NEGATIVE CONTACT PLATE AND INSULATES IT FROM POSITIVE CASE)
HgO CONTACTS BOTTOM OF CASE
STEEL CASE SERVES AS POSITIVE TERMINAL
(B)

Figure 2-5.—Size and construction of typical mercury (RM) cells.

Mercury cells, as compared to lead-acid cells, are also quite different in their internal construction, as shown by the exploded view in figure 2-5 (B). The negative electrode is corrugated zinc foil, spirally co-wrapped with an inert separator. The zinc is coated with pure mercury (amalgamated) to prevent local action during shelf storage. In the completed cell, the top contact plate connects to the spiralled edge of the zinc foil. The bottom of the separator rests against the mercuric oxide pellet; and the pellet is, in turn, pressed tightly against the bottom of the steel case. There is space in the foil corrugations and in the clearance between the foil and HgO pellet. This space is filled with electrolyte. The electrolyte is an alkaline solution of potassium hydroxide, zincate, and water. The cell is sealed, since there is no gassing during discharge.

The overall chemical action by which the mercury cell produces electricity is given by the following chemical formula:

$$Zn + H_2O + HgO \longrightarrow ZnO + H_2O + Hg.$$

This action, the same as in other type cells, is a process of oxidation. The alkaline electrolyte is in contact with the zinc electrode. The zinc oxidizes (Zn changes to ZnO), thus taking atoms of oxygen from water molecules in the electrolyte. This leaves positive hydrogen ions, which move toward the mercuric oxide pellet, causing polarization. These hydrogen ions take oxygen from the mercuric oxide (thus changing HgO to Hg). Where one molecule of water is destroyed at the negative electrode, one molecule is produced at the positive electrode, maintaining the net amount of water constant. By absorbing oxygen, the zinc electrode accumulates excess electrons, making it negative. By giving up oxygen, the mercuric oxide electrode loses electrons, making it positive. In the discharged state, the negative electrode is zinc oxide, and the positive electrode is ordinary mercury.

Reserve Cell

A reserve cell is one in which the elements are kept dry until the time of use at which time the electrolyte is admitted and the cell starts producing current. The rigorous requirements of the proximity fuse led to the development of this type of cell. In the proximity fuse the battery consists of 63 annular (or ring-shaped) zinc and carbon electrodes. A glass container is mounted in the center of the electrodes. The shock of the acceleration produced by firing the shell breaks the glass container and forces the electrolyte between the electrodes, thus activating the cell.

The shelf life of primary reserve batteries is extremely long even under adverse tropic or arctic conditions. This life is attained by incorporating the depolarizer in the liquid electrolyte so that the elements of the cell are subject to no chemical action until the time of use.

Combining Cells

In many cases, a battery-powered device may require more electrical energy than one cell can provide. The device may require either a higher voltage or more current, and in some cases both. Under such conditions it is necessary to combine, or interconnect, enough cells to meet the higher requirements. Cells connected in series provide a higher voltage, while cells connected in parallel provide a higher current capacity. To provide adequate power when both voltage and current requirements are greater than one cell's capacity, a combination series-parallel network of cells must be interconnected.

SERIES-CONNECTED CELLS

Assume you must connect enough No. 6 dry cells to supply power to a load requiring 6 volts. At this potential, the load will draw 1/8 ampere. Since a single No. 6 cell supplies a potential of only 1.5 volts, more than one cell is obviously needed. To obtain the higher potential, the cells are connected in series as shown in figure 2-6 (A).

In a series hookup, the negative electrode of the first cell is connected to the positive electrode of the second cell, the negative electrode of the second to the positive of the third, and so on. The positive electrode of the first cell and negative electrode of the last cell then serve as the power takeoff terminals of the battery. In this way, the potential is boosted 1.5 volts by each cell in the series line. There are four cells, so the output terminal voltage is 1.5 x 4 = 6 volts. When connected to the load, 1/8 ampere flows through the load and each cell of the battery. This is within the capacity of each No. 6 cell. Therefore, only four series-connected No. 6 cells are needed to supply this particular load.

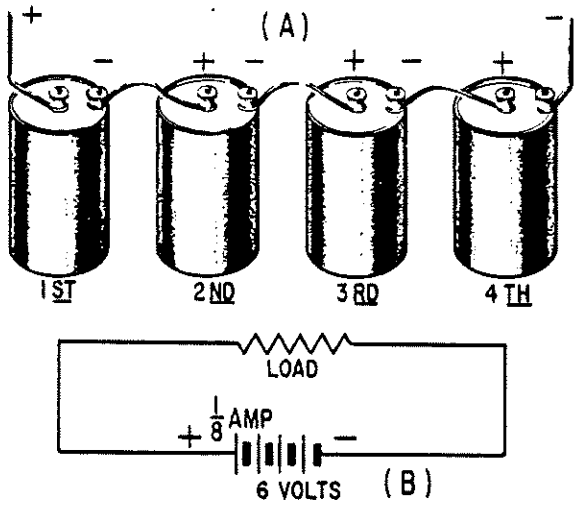


Figure 2-6.–(A) Pictorial view of series-connected cells; (B) schematic of series connection.

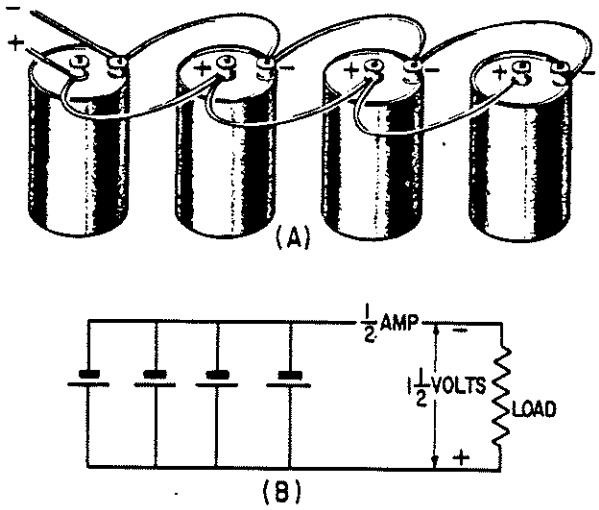


Figure 2-7.–(A) Pictorial view of parallel-connected cells; (B) schematic of parallel connections.

PARALLEL-CONNECTED CELLS

In this case, assume an electrical load requires only 1.5 volts, but will draw 1/2 ampere of current. (Assume that a No. 6 cell will supply only 1/8 ampere.) To meet this requirement, the No. 6 cells are connected in parallel, as shown in figure 2-7 (A). In a parallel connection, all positive cell electrodes are connected to one line, and all negative electrodes are connected to the other. No more than one cell is connected between the lines at any one point, so the potential between the lines is the same as that of one cell, or 1.5 volts. However, each cell may contribute its maximum allowable current of 1/8 ampere to the line. There are four cells, so the total line current is 1/8 x 4 = 1/2 ampere. Hence, four No. 6 cells in parallel have enough capacity to supply a load requiring 1/2 ampere at 1.5 volts.

SERIES-PARALLEL CONNECTED CELLS

Figure 2-8 depicts a battery network supplying power to a load requiring both a voltage and current greater than one cell can provide. To provide the required 4-1/2 volts, groups of three 1.5-volt cells are connected in series. To provide the required 1/2 ampere of current, four series groups are connected in parallel, each supplying 1/8 ampere of current.

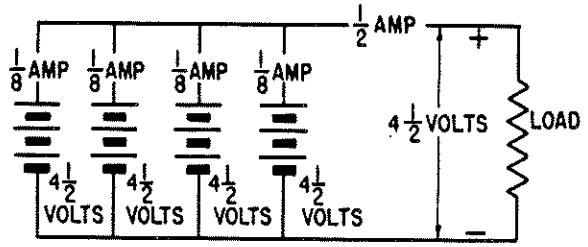


Figure 2-8.–Series-parallel connected cells.

SECONDARY (WET) CELLS

Secondary cells function on the same basic chemical principles as primary cells. They differ mainly in that they may be recharged, whereas the primary cell is not rechargeable. Some of the materials of a primary cell are consumed in the process of changing chemical energy to electrical energy. In the secondary cell, the materials are merely transferred from one electrode to the other as the cell discharges. Discharged secondary cells may be restored (charged) to their original state by forcing an electric current from some other source through the cell in the opposite direction to that of discharge.

The storage battery consists of a number of secondary cells connected in series. Properly speaking, this battery does not store electrical energy, but is a source of chemical energy which produces electrical energy. There are three

types of storage cells--the lead-acid type, which has an e.m.f. of 2.2 volts per cell; the nickel-iron-alkali type; and the nickel-cadmium-alkaline type. The latter two have an e.m.f. of 1.2 volts per cell. Of these three types, the lead-acid type is the most widely used, and will be described first.

Lead-Acid Batteries

In its charged condition, the active materials in the lead-acid battery are lead peroxide (used as the positive plate) and sponge lead (used as the negative plate). The electrolyte is a mixture of sulfuric acid and water. The strength (acidity) of the electrolyte is measured in terms of its specific gravity. Specific gravity is the ratio of the weight of a given volume of electrolyte to an equal volume of pure water. Concentrated sulfuric acid has a specific gravity of about 1.830; pure water has a specific gravity of 1.000. The acid and water are mixed in a proportion to give the specific gravity desired. For example, an electrolyte with a specific gravity of 1.210 requires roughly one part of concentrated acid to four parts of water.

In a fully charged battery the positive plates are pure lead peroxide and the negative plates are pure lead. Also, in a fully charged battery, all the acid is in the electrolyte so that the specific gravity is at its maximum value. The active materials of both the positive and negative plates are porous, and have absorptive qualities similar to a sponge.

The pores are therefore filled with the battery solution (electrolyte) in which they are immersed. As the battery discharges, the acid in contact with the plates separates from the electrolyte. It forms a chemical combination with the plate's active material, changing it to lead sulfate. Thus, as the discharge continues, lead sulfate forms on the plates, and more acid is taken from the electrolyte. The electrolyte's water content becomes progressively higher; that is, the ratio of water to acid increases. As a result, the specific gravity of the electrolyte will gradually decrease during discharge.

When the battery is being charged, the reverse takes place. The acid held in the sulfated plate material is driven back into the electrolyte; further charging cannot raise its specific gravity any higher. When fully charged, the material of the positive plates is again pure lead peroxide and that of the negative plates is pure lead.

Electrical energy is derived from a cell when the plates react with the electrolyte. As a molecule of sulfuric acid separates, part of it combines with the negative sponge lead plates. Thus, it makes the sponge lead plates negative, and at the same time forms lead sulfate. The remainder of the sulfuric acid molecule, lacking electrons, has thus become a positive ion. The positive ions migrate through the electrolyte to the opposite (lead peroxide) plates, and takes electrons from them. This action neutralizes the positive ions, forming ordinary water. It also makes the lead peroxide plates positive, by taking electrons from them. Again, lead sulfate is formed in the process.

The action just described is represented in more detail by the following chemical equation

$$Pb + PbO_2 + 2H_2SO_4 \underset{\text{discharging}}{\rightleftharpoons} 2PbSO_4 + 2H_2O.$$

The left side of the expression represents the cell in the charged condition, and the right side represents the cell in the discharged condition.

In the charged condition the positive plate contains lead peroxide, PbO_2; the negative plate is composed of sponge lead, Pb; and the solution contains sulfuric acid, H_2SO_4. In the discharged condition both plates contain lead sulfate, $PbSO_4$, and the solution contains water, H_2O. As the discharge progresses, the acid content of the electrolyte becomes less and less because it is used in forming lead sulfate, and the specific gravity of the electrolyte decreases. A point is reached where so much of the active material has been converted into lead sulfate that the cell can no longer produce sufficient current to be of practical value. At this point the cell is said to be discharged (fig. 2-9 (C)). Since the amount of sulfuric acid combining with the plates at any time during discharge is in direct proportion to the ampere-hours (product of current in amperes and time in hours) of discharge, the specific gravity of the electrolyte is a guide in determining the state of discharge of the lead-acid cell.

If the discharged cell is properly connected to a direct-current charging source the voltage of which is slightly higher than that of the cell, current will flow through the cell, in the opposite direction to that of discharge, and the cell is said to be charging (fig. 2-9 (D)). The effect of the current will be to change the lead sulfate on both the positive and negative plates back to its original active form of lead peroxide and sponge

lead, respectively. At the same time, the sulfate is restored to the electrolyte with the result that the specific gravity of the electrolyte increases. When all the sulfate has been restored to the electrolyte, the specific gravity will be maximum. The cell is then fully charged and is ready to be discharged again.

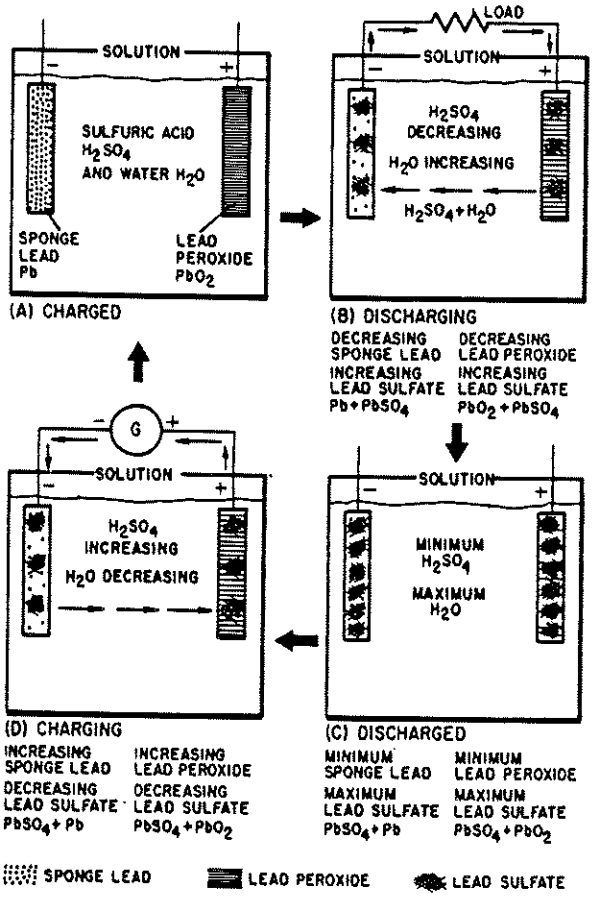


Figure 2-9.—Chemical action in lead-acid cell.

It should always be remembered that the addition of sulfuric acid to a discharged lead-acid cell does not recharge the cell. Adding acid only increases the specific gravity of the electrolyte and does not convert the lead sulfate on the plates back into active material (sponge lead and lead peroxide), and consequently does not bring the cell back to a charged condition. A charging current must be passed through the cell to do this.

As a cell charge nears completion, hydrogen gas, H_2, is liberated at the negative plate and oxygen gas, O_2, is liberated at the positive plate. This action occurs because the charging current is greater than the amount that is necessary to reduce the small remaining amount of lead sulfate on the plates. Thus, the excess current ionizes the water in the electrolyte. This action is necessary to assure full charge to the cell.

PASTED PLATES

Lead-acid storage batteries use a variety of plates ranging from the spun-lead (Plante) type to the lighter pasted construction. The Plante-type plates require repeated charging and discharging to develop the active material to the proper depth. The process is slow and expensive. In 1881 Camille Faure in France made a radical improvement in the construction of storage batteries by developing a pasted plate that was manufactured with much less expense.

The pasted plate is most commonly used in portable lead-acid batteries today. The plates are formed by applying special lead-oxide pastes to a grid made of lead-antimony alloy. The grid holds in place the active material with which the spaces in the grid are filled and distributes the current evenly to all parts of the plate.

When the paste is dry, the plates are given a forming charge. They are formed by immersing them in electrolyte and passing current through them in the proper direction to change the paste to lead peroxide for the positive plates and to sponge lead for the negative plates. This type of plate takes less time to manufacture and is relatively light in weight compared to the Plante spun-lead plates, which have a more rugged and durable construction.

IRONCLAD PLATE

The ironclad plate is used extensively in submarine batteries because it has a long life. The positive ironclad plate (fig. 2-10 (A)) is quite different from the pasted plate. It consists of several slotted hard-rubber tubes filled with active material that is similar to the material used in the pasted plate. Extending through the center of each tube is a core of lead antimony, which is firmly anchored in the paste by means of radial fins that are equally spaced along the core. The core, which is lead-burned to the top and bottom of the frame, serves primarily as a conductor for the electric current and strengthens the plate. Lead-antimony cores form the

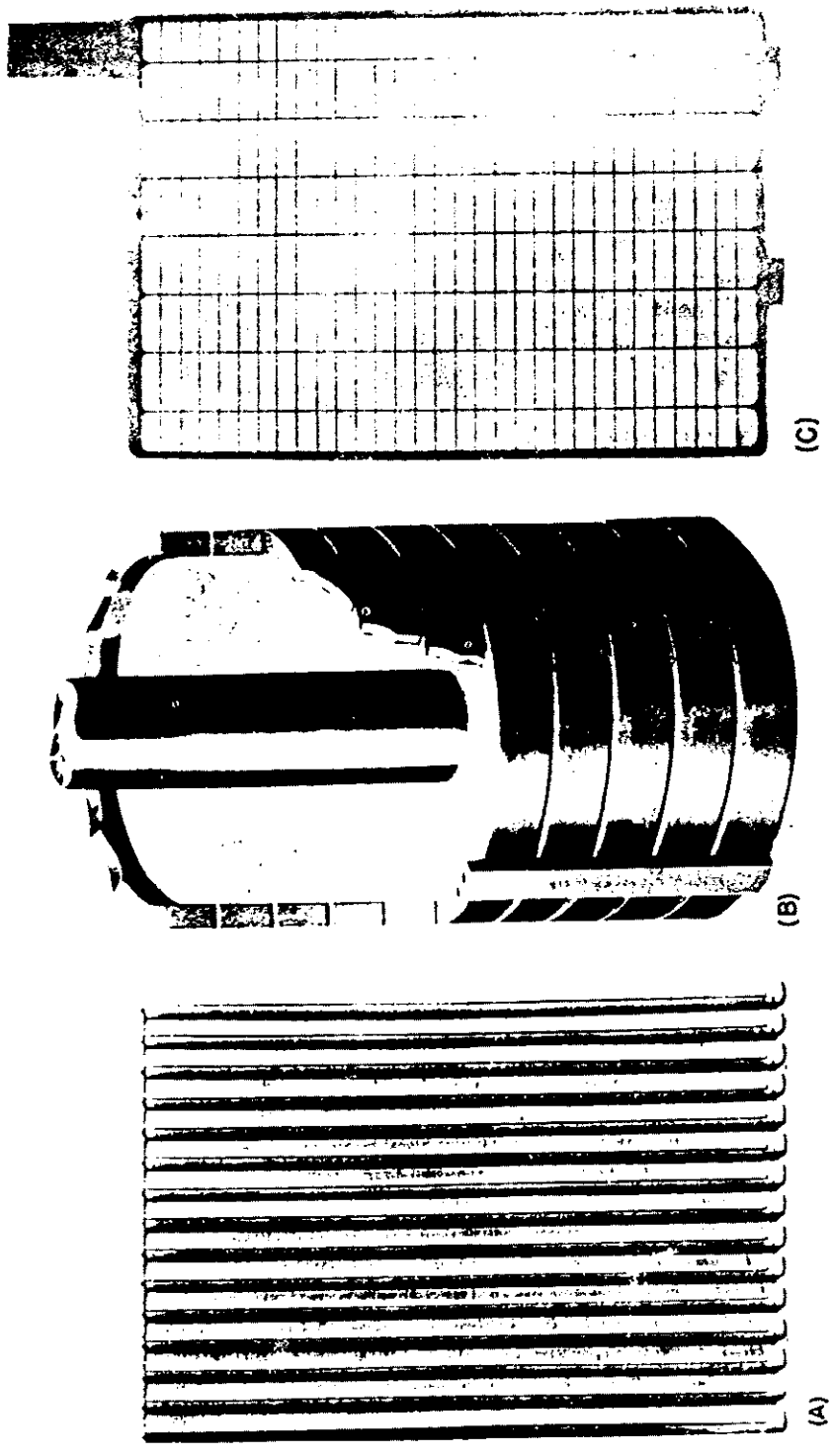


Figure 2-10.—Ironclad plate construction.

grids that comprise the conducting network between the hard-rubber tubes of the positive plate.

The hard-rubber tubes contain narrow horizontal slots to permit the passage of electrolyte through them so that it may come into contact with the active material inside the tubes (fig. 2-10 (B)).

The slotted tubes prevent the washing away, or shedding, of the active material. Each tube has two full-length ribs--one on each side--which keep the separators (spacers) from covering the slots and preventing the electrolyte from circulating freely. The ironclad negative plates are essentially the same as the negative pasted plates (fig. 2-10 (C)).

GOULD PLATE

The Gould Plate is a pasted plate that differs very little from the ordinary positive and negative pasted plates. A glass-wool mat directly over the positive plate holds the active material in place. Rubber or wood separators are used as in other batteries. The glass-wool mat prevents shedding amd makes the Gould battery almost as durable as the ironclad battery. Hence the Gould battery is used extensively in both submarines and surface vessels.

LEAD-ACID CELL ELEMENT

The plates are formed into positive and negative groups. When these groups are assembled, they become a cell element (fig. 2-11). The number of negative plates is always one more than the number of positive plates so that both sides of each positive plate are acted upon chemically. The active material on the positive plates expands and contracts as the battery is charged and discharged. The expansion and contraction must be kept the same on both sides of the plates to prevent buckling.

Separators of wood, rubber, or glass are placed between the positive and negative plates to act as insulators (fig. 2-11). These separators are grooved vertically on one side and are smooth on the other. The grooved side is placed next to the positive plate to permit free circulation of the electrolyte around the active material.

An assembled lead-acid cell with the positive and negative terminals projecting through the cell cover is shown in figure 2-12. A hole fitted with a filler cap is provided in each cell cover to permit filling and testing. The filler cap has a vent hole to allow the gas that forms in the cell during charge to escape.

The ordinary 6-volt portable storage battery consists of 3 cells assembled in a molded hard-rubber (monobloc) case. Metal cannot be used

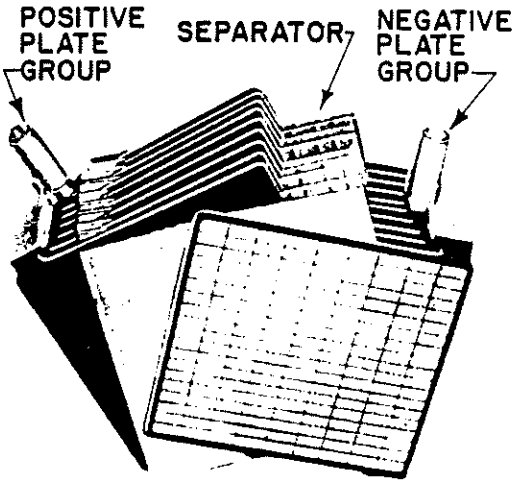


Figure 2-11.—Partly assembled cell element.

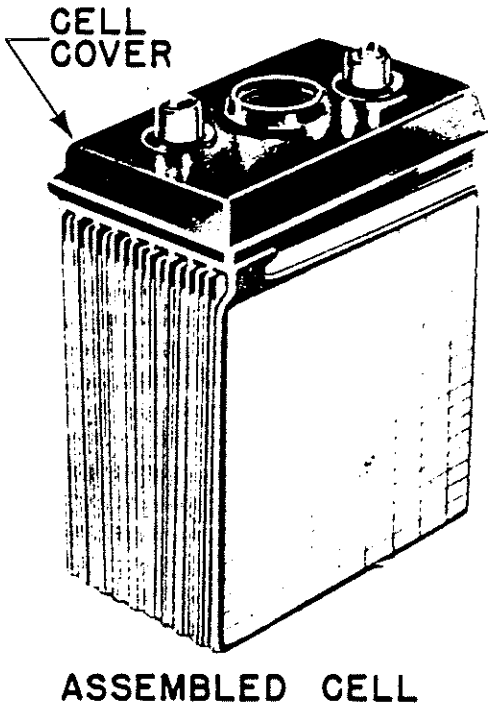


Figure 2-12.—Assembled lead-acid cell.

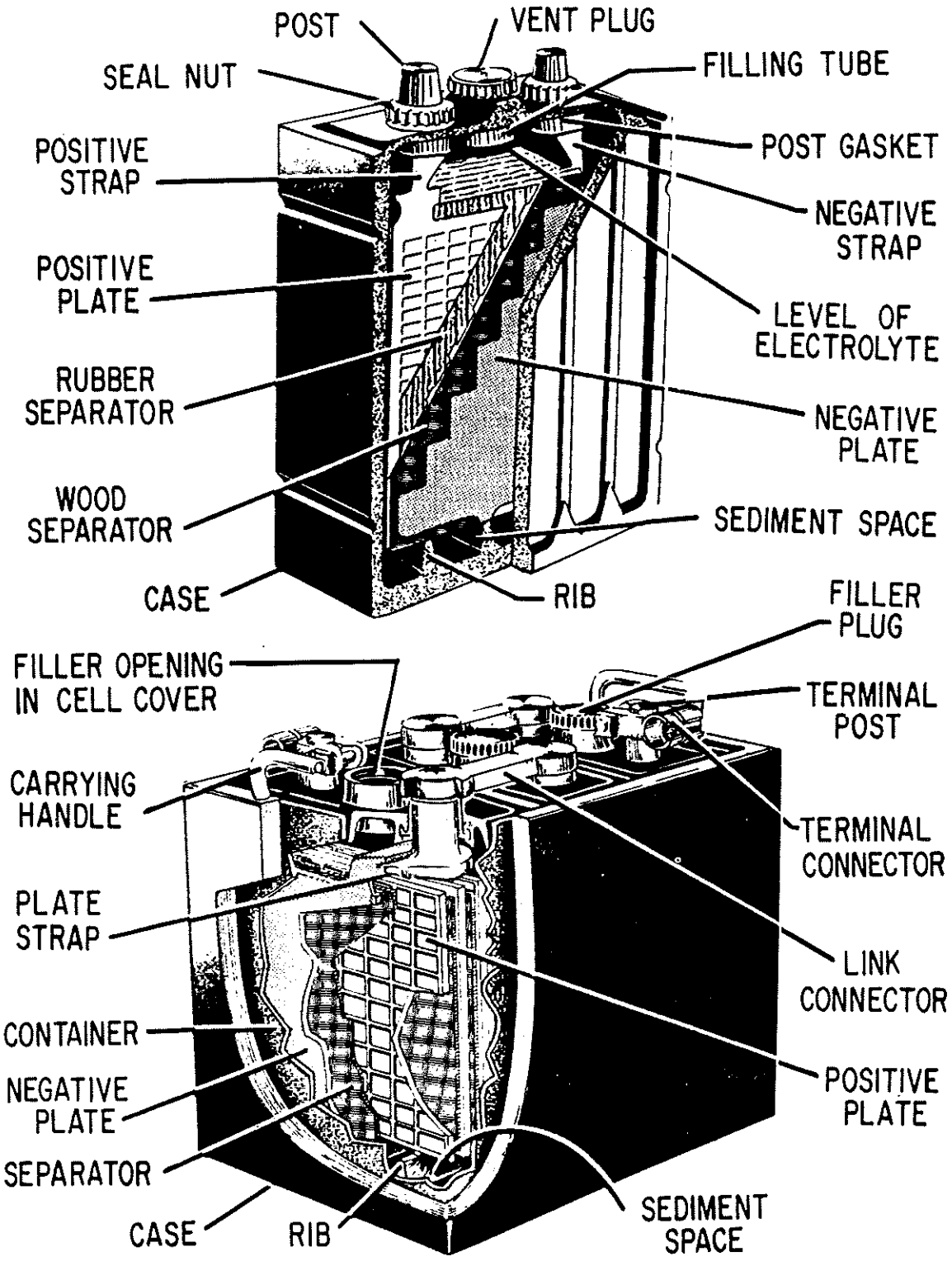


Figure 2-13.–Lead-acid cell and battery.

because of the acid electrolyte. Each cell is contained in an acidproof compartment within the case. The cells are connected in series by means of lead-alloy connectors that are attached to the terminal posts of adjacent cells by a lead-burning process. The space between the case and the edges of the cell covers is filled with an acidproof battery-sealing compound, or pitch. This compound is a blend of bituminous materials that are processed so that they remain solid at high temperatures and do not crack at low temperatures.

Figure 2-13 shows a cutaway view of a lead-acid cell and a battery.

SPECIFIC GRAVITY

The ratio of the weight of a certain volume of liquid to the weight of the same volume of water is called the specific gravity of the liquid. The specific gravity of pure water is 1.000. Sulfuric acid has a specific gravity of 1.830; thus sulfuric acid is 1.830 times as heavy as water. The specific gravity of a mixture of sulfuric acid and water varies with the strength of the solution from 1.000 to 1.830.

As a storage battery discharges, the sulfuric acid is depleted and the electrolyte is gradually converted into water. This action provides a guide in determing the state of discharge of the lead-acid cell. The electrolyte that is usually placed in a lead-acid battery has a specific gravity of 1.350 or less. Generally, the specific gravity of the electrolyte in Navy portable batteries is adjusted between 1.210 and 1.220. On the other hand the specific gravity of the electrolyte in submarine batteries when charged is from 1.250 to 1.265, while in aircraft batteries when fully charged it is from 1.285 to 1.300.

Hydrometer

The specific gravity of the electrolyte is measured with a hydrometer. In the syringe-type hydrometer (fig. 2-14), part of the battery electrolyte is drawn up into a glass tube by means of a rubber bulb at the top.

The hydrometer float consists of a hollow glass tube weighted at one end and sealed at both ends. A scale calibrated in specific gravity is laid off axially along the body (stem) of the tube. The hydrometer float is placed inside the glass syringe and the electrolyte to be tested is drawn up into the syringe, thus immersing the hydrometer float into the solution. When the syringe is held approximately in a vertical position, the hydrometer float will sink to a certain level in the electrolyte. The extent to which the hydrometer stem protudes above the level of the liquid depends upon the specific gravity of the solution.

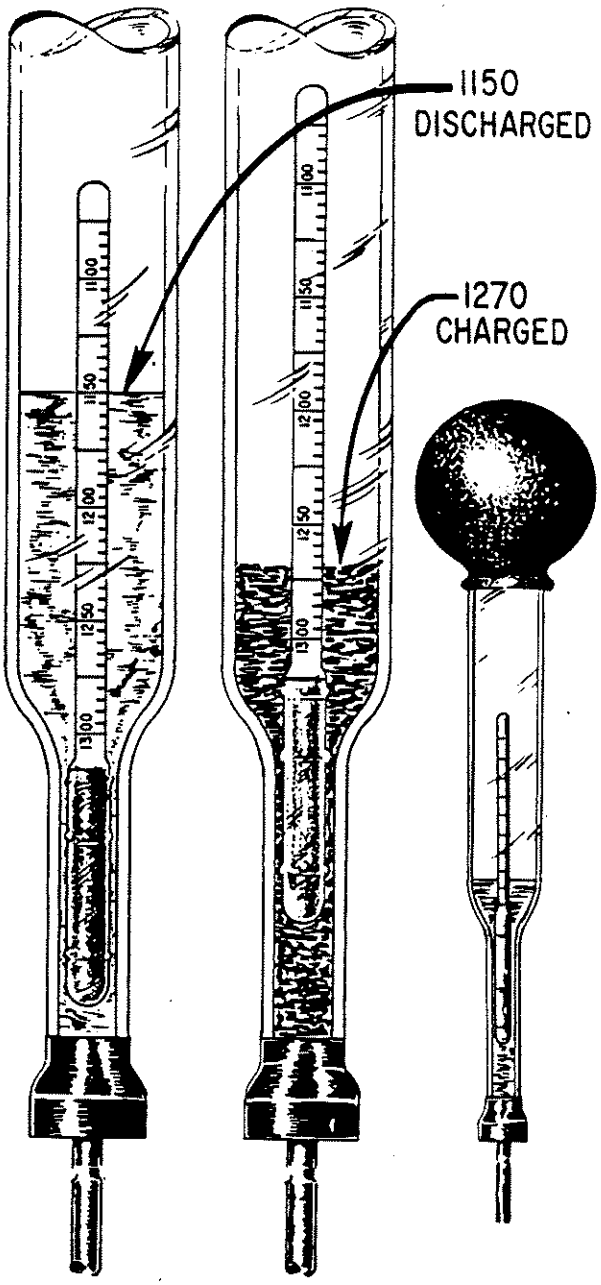


Figure 2-14.—Type-B hydrometer.

MIXING ELECTROLYTES

The electrolyte of a fully charged battery usually contains about 38 percent sulfuric acid by weight, or about 27 percent by volume. In preparing the electrolyte distilled water and sulfuric acid that meets Navy specifications are used. New batteries may be delivered with containers of concentrated sulfuric acid of 1.830 specific gravity or electrolyte of 1.400 specific gravity, both of which must be diluted with distilled water to make electrolyte of the proper specific gravity. The container used for diluting the acid should be made of glass, earthenware, rubber, or lead.

When mixing electrolyte, ALWAYS POUR ACID INTO WATER—never pour water into acid. Pour the acid slowly and cautiously to prevent excessive heating and splashing. Stir the solution continuously with a nonmetallic rod to mix the heavier acid with the lighter water and to keep the acid from sinking to the bottom. When concentrated acid is diluted, the solution becomes very hot.

TREATMENT OF ACID BURNS

If acid or electrolyte from a lead-acid battery comes into contact with the skin, the affected area should be washed as soon as possible with large quantities of fresh water, after which a salve such as vaseline, boric acid, or zinc ointment should be applied. If none of these salves are available, clean lubricating oil will suffice. When washing, large amounts of water should be used, since a small amount of water might do more harm than good in spreading the acid burn.

Acid spilled on clothing may be neutralized with dilute ammonia or a solution of baking soda and water.

CAPACITY

The capacity of a battery is measured in ampere-hours. As mentioned before, the ampere-hour capacity is equal to the product of the current in amperes and the time in hours during which the battery is supplying this current. The ampere-hour capacity varies inversely with the discharge current. The size of a cell is determined generally by its ampere-hour capacity. The capacity of a cell depends upon many factors, the most important of which are (1) the area of the plates in contact with the electrolyte; (2) the quantity and specific gravity of the electrolyte; (3) the type of separators; (4) the general condition of the battery (degree of sulfating, plates buckled, separators warped, sediment in bottom of cells, and so forth); and (5) the final limiting voltage.

TYPES OF CHARGES

The following types of charges may be given to a storage battery, depending upon the condition of the battery: (1) Initial charge, (2) normal charge, (3) equalizing charge, (4) floating charge, and (5) emergency charge.

Initial Charge

When a new battery is shipped dry, the plates are in an uncharged condition. After the electrolyte has been added, it is necessary to convert the plates into the charged condition. This is accomplished by giving the battery a long low-rate INITIAL CHARGE. The charge is given in accordance with the manufacturer's instructions, which are shipped with each battery. If the manufacturer's instructions are not available, reference should be made to the detailed instruction in current bureau directives.

Normal Charge

A normal charge is a routine charge that is given in accordance with the nameplate data during the ordinary cycle of operation to restore the battery to its charged condition. The following steps should be observed:

1. Determine the starting and finishing rate from the nameplate data.
2. Add water, as necessary, to each cell.
3. Connect the battery to the charging panel and make sure the connections are clean and tight.
4. Turn on the charging circuit and set the current through the battery at the value given as the starting rate.
5. Check the temperature and specific gravity of pilot cells hourly.
6. When the battery begins to gas freely, reduce the charging current to the finishing rate.

A normal charge is complete when the specific gravity of the pilot cell, corrected for temperature, is within 5 points (0.005) of the specific gravity obtained on the previous equalizing charge.

Equalizing Charge

An equalizing charge is an extended normal charge at the finishing rate. It is given periodically to insure that all the sulfate is driven from the plates and that all the cells are restored to a maximum specific gravity. The equalizing charge is continued until the specific gravity of all cells, corrected for temperature, shows no change for a 4-hour period. Readings of all cells are taken every half hour.

Floating Charge

A battery may be maintained at full charge by connecting it across a charging source that has a voltage maintained within the limits of from 2.13 to 2.17 volts per cell of the battery. In a floating charge the charging rate is determined by the battery voltage rather than by a definite current value. The voltage is maintained between 2.13 and 2.17 volts per cell with an average as close to 2.15 volts as possible.

Emergency Charge

An emergency charge is used when a battery must be recharged in the shortest possible time. The charge starts at a much higher rate than is normally used for charging. It is seldom used because spare batteries are provided for all battery-operated equipment and this type charge may be harmful to the battery.

CHARGING RATE

The charging rate of every Navy storage battery is given on the battery nameplate. If the available charging equipment does not have the desired charging rates, the nearest available rates should be used. However, the rate should never be so high that violent gassing occurs. NEVER ALLOW THE TEMPERATURE OF THE ELECTROLYTE IN ANY CELL TO RISE ABOVE 125° F.

GASSING

When a battery is being charged, a portion of the energy is dissipated in the electrolysis of the water in the electrolyte. Thus, hydrogen is released at the negative plates and oxygen at the positive plates. These gases bubble up through the electrolyte and collect in the air space at the top of the cell. If violent gassing occurs when the battery is first placed on charge, the charging rate is too high. If the rate is not too high, steady gassing, which develops as the charging proceeds, indicates that the battery is nearing a fully charged condition. A mixture of hydrogen and air can be dangerously explosive. No smoking, electric sparks, or open flames should be permitted near charging batteries.

Nickel-Cadmium Cell

The nickel-cadmium cell is an alkaline storage cell. It is used in aircraft and in the Nike and Corporal guided missiles, and may be installed aboard ship in the foreseeable future. The construction and general arrangement of the cell are similar to that of the lead-acid cell. The negative plate assembly is a cadmium-oxide compound; the positive plate assembly is a nickel-oxide compound; and the electrolyte is a 30 percent solution of potassium hydroxide (KOH). Separators between the positive and negative groups prevent internal short circuits. The cell components are assembled in a single plastic jar. The battery case is of fabricated steel. A 6-volt battery contains 5 series-connected cells. When fully charged, the cell voltage ranges from 1.39 to 1.45 volts.

The nickel-cadmium battery used in some naval aircraft is interchangeable with the present aviation type lead-acid batteries. The nickel-cadmium and lead-acid batteries have capacities that are comparable at normal discharge rates, but at high discharge rates nickel-cadmium batteries have a higher capacity. The lead-acid aircraft battery is comprised of 12 cells with a nominal cell voltage of 2 volts, while the nickel-cadmium battery contains 20 cells with a nominal voltage of 1.4 volts per cell.

CHARGING

The effect of the charging current is to change the active material of the negative plate (cadmium-oxide) to metallic cadmium (CdO to Cd). The active material of the positive plate (nickel-oxide) is changed to a higher state of

oxidation (NiO to Ni_2O_3). As long as the charging current continues, this action occurs until both materials are completely converted. Toward the end of the charging process and during overcharge, the cell will gas due to the electrolysis of the water in the electrolyte. This action liberates 4 atoms of hydrogen gas ($2H_2$) at the negative plate for every 2 atoms of oxygen gas (O_2) liberated at the positive plate. The amount of gas liberated depends on the charging rate.

The electrolyte does not enter into any chemical reaction with the positive or negative plates. It acts simply as a conductor of current between the plates, and its specific gravity does not vary appreciably with the amount of charge. The effect of the reactions during charge is a transfer of oxygen from the negative to the positive plates. In this respect the nickel-cadmium storage battery is similar to the lead-acid storage battery. Unlike the lead-acid storage battery the specific gravity of the electrolyte remains constant, except at the end of a charge or on overcharge, when it increases because of the electrolysis of the water. The proper specific gravity can be obtained by adding distilled water.

Nickel-cadmium batteries can be charged by the (1) constant voltage, (2) constant current, and (3) stepped constant-current methods. The most efficient performance is obtained when the charging rate is such that 140 percent of the rated ampere-hour capacity of the cell is delivered to the cell within a 3-hour interval.

DISCHARGING

When the cell is connected to an external circuit containing a resistance, the chemical action which occurs is the reverse to that of the charging process. The negative plate gradually regains oxygen (Cd to CdO), and the positive plate gradually loses oxygen (Ni_2O_3 to NiO); that is, the action during discharge effects a transfer of oxygen from the positive to the negative plates. There is no gassing on discharge due to the interchange of oxygen. The discharge process is the conversion of the chemical energy of the plates into electrical energy. The rate at which this conversion occurs is determined by the external resistance, or load, to which the battery is connected. The internal resistance of the cell is extremely low because of the cell construction.

The nickel-cadmium battery is smaller and weighs less than the comparable lead-acid battery. There is little or no local action, and the positive plates do not shed, or flake off, as do the positive plates in the lead-acid cell. The battery life is from 10 to 15 years with constant capacity over the entire period, and satisfactory operation can be obtained over a temperature range from -65° F. to 165° F.

Silver-Zinc Batteries

Silver-zinc batteries are presently used in guided missiles. These batteries are made up of cells that are classed as "reserve cells." As stated previously, a reserve cell is one which is maintained in the dry state until power is needed. At this time, the cell is activated by adding the electrolyte solution. Once the solution has been added, the battery requires no further charging. However, once activated, the silver-zinc battery must be used immediately because it has an extremely short shelf life. This battery is also quite expensive, due to its silver content.

The physical construction of these batteries is such that they are able to withstand high accelerations and to operate effectively in spite of the shock, vibration, and extreme temperature variations present in missile flight. Other advantages also tend to offset the cost and shelf-life restrictions. Two of the major advantages are (1) the high power-to-weight ratio of silver-zinc batteries and (2) their high discharge rate while maintaining a nearly flat voltage. That is, they are able to expend their energy at a high rate over a short period of time, as in the brief flight of a missile.

In the charged or "ready" state, the positive electrode material is silver peroxide, Ag_2O_2. The negative electrode is zinc, Zn, and the electrolyte is mainly potassium hydroxide, KOH. In discharging, the silver peroxide changes to a lower state of oxidation, becoming silver oxide, Ag_2O. In giving up oxygen atoms, the silver peroxide also loses electrons, thus becoming positive. The zinc electrode, in oxidizing (absorbing oxygen), accumulates excess electrons, and thus becomes negative. Water in the electrolyte is destroyed at the negative electrode, and formed at the positive electrode, with the net amount of water remaining constant.

QUIZ

1. The dry cell battery is a
   a. secondary cell
   b. polarized cell
   c. primary cell
   d. voltaic cell

2. The electrolyte of a lead-acid wet cell is
   a. sal ammoniac
   b. manganese dioxide
   c. sulfuric acid
   d. distilled water

3. A battery which can be restored after discharge is a
   a. primary cell
   b. galvanic cell
   c. dry cell
   d. secondary cell

4. Lead-acid battery plates are held together by a
   a. glass wool mat
   b. wood separators
   c. grid work
   d. hard rubber tube

5. When mixing electrolyte, always pour
   a. water into acid
   b. acid into water
   c. both acid and water into vat simultaneously
   d. any of the above are correct

6. When charging a battery, the electrolyte should never exceed a temperature of
   a. 125° F.
   b. 113° F.
   c. 80° F.
   d. 40° F.

7. The plates of a lead-acid battery are made of
   a. lead and lead dioxide
   b. lead and lead oxide
   c. silver and peroxide
   d. lead and lead peroxide

8. A battery is receiving a normal charge. It begins to gas freely. The charging current should
   a. be increased
   b. be decreased
   c. be cut off and the battery allowed to cool
   d. remain the same

9. A hydrometer reading is 1.265 at 92° F. The corrected reading is
   a. 1.229
   b. 1.261
   c. 1.269
   d. 1.301

10. In the nickel-cadmium battery, KOH is
    a. the positive plate
    b. the negative plate
    c. the electrolyte
    d. none of the above

11. When sulfuric acid, H_2SO_4, and water, H_2O, are mixed together, they form a
    a. gas
    b. compound
    c. mixture
    d. hydrogen solution

12. How many No. 6 dry cells are required to supply power to a load requiring 6 volts, if the cells are connected in series?
    a. Two
    b. Four
    c. Five
    d. Six

13. The ordinary 6-volt lead-acid storage battery consists of how many cells?
    a. Two
    b. Three
    c. Four
    d. Six

14. A fully charged aircraft battery has a specific gravity reading of
    a. 1.210 to 1.220
    b. 1.250 to 1.265
    c. 1.285 to 1.300
    d. 1.300 to 1.320

15. What is the ampere-hour rating of a storage battery that can deliver 20 amperes continuously for 10 hours?
    a. 20 ampere-hour
    b. 40 ampere-hour
    c. 200 ampere-hour
    d. 400 ampere-hour

16. The normal cell voltage of a fully charged nickel-cadmium battery is
    a. 2.0 volts
    b. 1.5 volts
    c. 1.4 volts
    d. 1.0 volts

17. The electrolyte in a mercury cell is
    a. sulfuric acid
    b. KOH
    c. potassium hydroxide, zincate, and mercury
    d. potassium hydroxide, water, and zincate

18. Concentrated sulfuric acid has a specific gravity of
    a. 1.285
    b. 1.300
    c. 1.830
    d. 2.400

19. The number of negative plates in a lead-acid cell is always
    a. one greater than the number of positive plates
    b. equal to the number of positive plates
    c. one less than the number of positive plates
    d. double the number of positive plates

20. A lead-acid battery is considered fully charged when the specific gravity readings of all cells taken at half-hour intervals show no change for
    a. four hours
    b. three hours
    c. two hours
    d. one hour

CHAPTER 3
THE SIMPLE ELECTRIC CIRCUIT

Whenever two unequal charges are connected by a conductor, a complete pathway for current flow exists. Current will flow from the negative to the positive charge. This was illustrated in chapter 1.

An electric circuit is a completed conducting pathway, consisting not only of the conductor, but including the path through the voltage source. Current flows from the positive terminal through the source, emerging at the negative terminal. As an example, a lamp connected by conductors across a dry cell forms a simple electric circuit. (Refer to fig. 3-1.)

Current flows from the (-) terminal of the battery through the lamp to the (+) battery terminal, and continues by going through the battery from the (+) to the (-) terminal. As long as this pathway is unbroken, it is a closed circuit and current will flow. However, if the path is broken at ANY point, it is an open circuit and no current flows.

Current flow in the external circuit is the movement of electrons in the direction indicated by the arrows (from the negative terminal through the lamp to the positive terminal). (See fig. 3-1 (A)). Current flow in the internal battery circuit is the simultaneous movement in opposite directions of positive hydrogen ions toward the positive terminal of the battery and negative ions toward the negative terminal.

A closed loop of wire (conductor) is not necessarily a circuit. A source of voltage must be included to make it an electric circuit. In any electric circuit where electrons move around a closed loop, current, voltage, and resistance are present. The physical pathway for current flow is actually the circuit. Its resistance controls the amount of current flow around the circuit. By knowing any two of the three quantities, such as voltage and current, the third (resistance) may be determined. This is done mathematically by the use of Ohm's law.

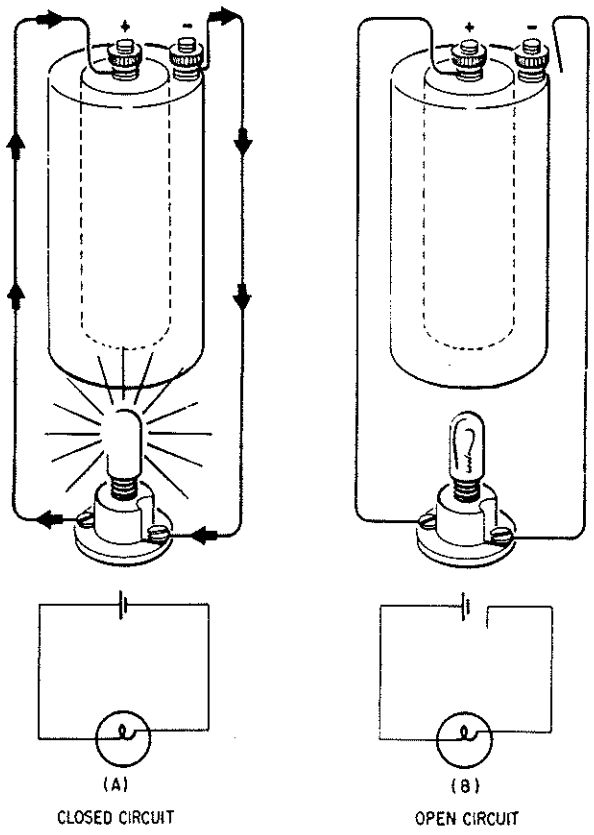


Figure 3-1.–(A) Simple electric circuit (closed); (B) simple electric circuit (open).

Ohm's Law

In the 19th century, a German philosopher, Georg Simon Ohm, proved by experiment the constant proportionally between electric current and voltage in the simple electric circuit and published the results of his findings in 1826. Ohm's law is fundamentally linear and therefore

simple. It is exact and applies to d-c circuits and devices in its basic form. In a modified form it may also be applied to a-c circuits. The unit of electrical resistance is called the OHM (designated by the Greek letter omega Ω) and finds wide application in the sources, loads, and conductors of electrical and electronic circuits.

MEANING OF OHM'S LAW

Ohm's law may be stated in words, as follows: THE INTENSITY OF THE CURRENT IN AMPERES IN ANY ELECTRIC CIRCUIT IS EQUAL TO THE DIFFERENCE IN POTENTIAL IN VOLTS ACROSS THE CIRCUIT DIVIDED BY THE RESISTANCE IN OHMS OF THE CIRCUIT.

Expressed as an equation, the law becomes

$$I = \frac{E}{R} \qquad (3\text{-}1)$$

where I is the intensity of the current in amperes, E the difference in potential in volts, and R the resistance in ohms.

If any two of these quantities are known, the third may be found by applying equation (3-1).

For example, if the voltage across the lamp in figure 3-2 is 12 volts and the effective resistance of the lamp is 2 ohms, the current through is will be $\frac{12}{2}$, or 6 amperes. If the effective resistance of the lamp remains constant

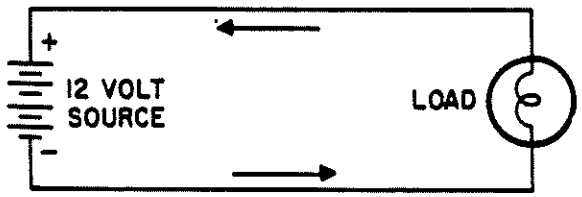


Figure 3-2.—Simple circuit.

at 2 ohms, in accordance with Ohm's law, the current will double if the voltage doubles, or halve if the voltage halves. In other words the CURRENT THROUGH THE LOAD WILL VARY DIRECTLY WITH THE VOLTAGE ACROSS THE LOAD. Thus, if the voltage across the load is reduced to zero, the current will equal $\frac{0}{2}$, or 0 amperes. If the voltage across the load is increased in steps of 1 volt starting at zero and continuing to 12 volts, the current through the load becomes $\frac{1}{2}$ = 0.5 ampere; $\frac{2}{2}$ = 1.0 ampere; $\frac{3}{2}$ = 1.5 ampere; and so forth.

The relation between current and voltage in this example is shown in figure 3-3 as a graph in which the voltage is plotted horizontally along the X axis to the right of the origin, and the corresponding values of current are plotted vertically along the Y axis above the origin.

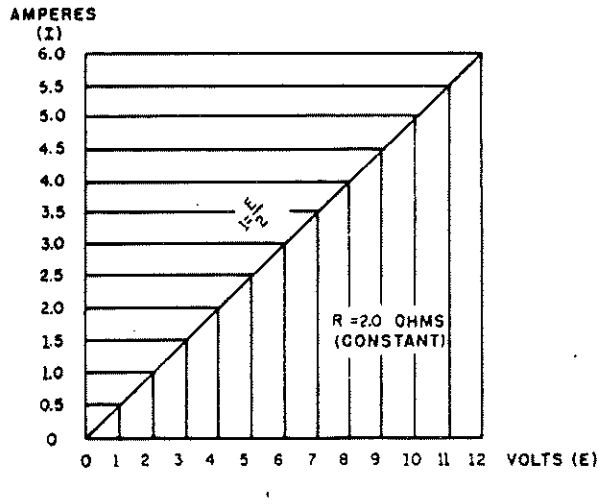


Figure 3-3.—Graph of voltage vs. current in a constant-resistance circuit.

The graph is a straight line, the equation of which is $I = \frac{E}{2}$. The constant, 2, represents the resistance in ohms of the circuit and is assumed not to change with the current in this example. This graph illustrates an important characteristic of the basic law—namely, the CURRENT VARIES DIRECTLY WITH THE APPLIED VOLTAGE IF THE RESISTANCE IS CONSTANT.

If the voltage across the load in figure 3-2 is maintained at a constant value of 12 volts, the current through the load will depend solely upon the effective resistance of the load. For example, if the resistance is 12 ohms, the current will be $\frac{12}{12}$, or 1 ampere. If the resistance is halved, the current will be doubled; if the resistance is doubled, the current will be halved. In other words, the current will vary inversely with the resistance.

If the resistance of the load is reduced in steps of 2 ohms starting at 12 ohms and continuing to 2 ohms, the current through the load

becomes $\frac{12}{10}$ = 1.2 amperes; $\frac{12}{8}$ = 1.5 amperes; $\frac{12}{6}$ = 2 amperes; and so forth. The relation between current and resistance in this example is expressed as a graph (fig. 3-4), whose equation is $I = \frac{12}{R}$. The numerator of the fraction represents a constant value of 12 volts in this example. As R approaches a small value the current approaches a very large value. The example illustrates a second equally important relation in Ohm's law—namely, that the CURRENT VARIES INVERSELY WITH THE RESISTANCE.

If the current through the load in figure 3-2 is maintained constant at 5 amperes, the voltage across the load will depend upon the resistance of the load and will vary directly with it. The relation between voltage and resistance is shown in the graph of figure 3-5. Values of resistance are plotted horizontally along the X axis to the right of the origin, and corresponding values of voltage are plotted vertically along the Y axis above the origin. The graph is a straight line having the equation $E = 5R$. The coefficient 5 represents the assumed current of 5 amperes which is constant in this example. Thus, a third important relation is illustrated—namely, that the VOLTAGE across a device VARIES DIRECTLY WITH THE EFFECTIVE RESISTANCE of the device provided the current through the device is maintained constant.

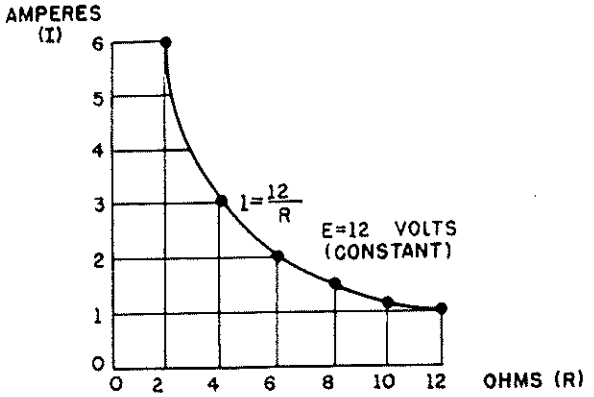


Figure 3-4.—Relation between current and resistance.

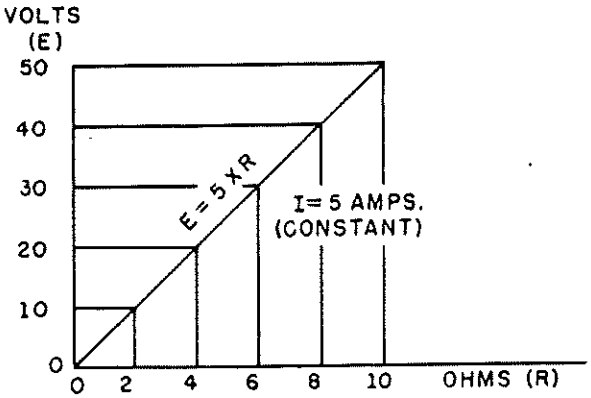


Figure 3-5.—Graph of voltage vs. resistance with constant current.

APPLYING OHM'S LAW

Equation (3-1) may be transposed to solve for the resistance if the current and voltage are known, or to solve for the voltage if the current and resistance are known. Thus, $R = \frac{E}{I}$ and $E = IR$. For example, if the voltage across a device is 50 volts and the current through it is 2 amperes, the resistance of the device will be $\frac{50}{2}$, or 25 ohms. Also, if the current through a wire is 3 amperes and the resistance of the wire is 0.5 ohm, the voltage drop across the wire will be 3 x 0.5, or 1.5 volts.

Equation (3-1) and its transpositions may be obtained readily with the aid of figure 3-6. The circle containing E, I, and R is divided into two parts with E above the line and IR below it. To determine the unknown quantity, first cover that quantity with a finger. The location of the

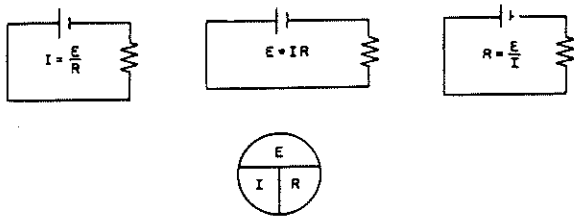


Figure 3-6.—Ohm's law in diagram form.

remaining uncovered letters in the circle will indicate the mathematical operation to be performed. For example, to find I, cover I with a finger. The uncovered letters indicate that E is to be divided by R, or $I = \frac{E}{R}$. To find E, cover E. The result indicates that I is to be multiplied by R, or $E = IR$. To find R, cover R. The result indicates that E is to be divided by I, or $R = \frac{E}{I}$.

Electric Power and Energy

POWER

Power, whether electrical or mechanical, pertains to the rate at which work is being done. Work is done whenever a force causes motion. If a mechanical force is used to lift or move a weight, work is done. However, force exerted WITHOUT causing motion, such as the force of a compressed spring acting between two fixed objects, does not constitute work.

Previously, you found that voltage is electrical force, and that voltage forces current to flow in a closed circuit. However, when voltage exists between two points, but current cannot flow, no work is done. This is similar to the spring under tension that produced no motion. When voltage causes electrons to move, work is done. The instantaneous RATE at which this work is done is called the electric power rate, and its measure is the watt.

A total amount of work may be done in different lengths of time. For example, a given number of electrons may be moved from one point to another in one second or in one hour, depending on the RATE at which they are moved. In both cases, total work done is the same. However, when the work is done in a short time, the wattage, or INSTANTANEOUS POWER RATE is greater than when the same amount of work is done over a longer period of time.

As stated, the basic unit of power is the WATT, and it is equal to the voltage across a circuit multiplied by current through the circuit. This represents the rate at any given instant at which work is being done in moving electrons through the circuit. The sympol P indicates electrical power. Thus, the basic power formula is $P = E \times I$. E is the voltage across and I is the current through the resistor or circuit whose power is being measured. The amount of power will change when either voltage or current, or both voltage and current change.

In addition, the Ohm's law equivalent of E is $I \times R$. If this equivalent is substituted for E, the power formula becomes

$$P = E \times I$$

$$P = (I \times R) \times I$$

$$P = I^2R$$

RATING OF ELECTRICAL DEVICES BY POWER

Electrical lamps, soldering irons, and motors are examples of electrical devices that are rated in watts. The wattage rating of a device indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion.

For example, a 100-watt lamp will produce a brighter light than a 75-watt lamp, because it converts more electrical energy into light.

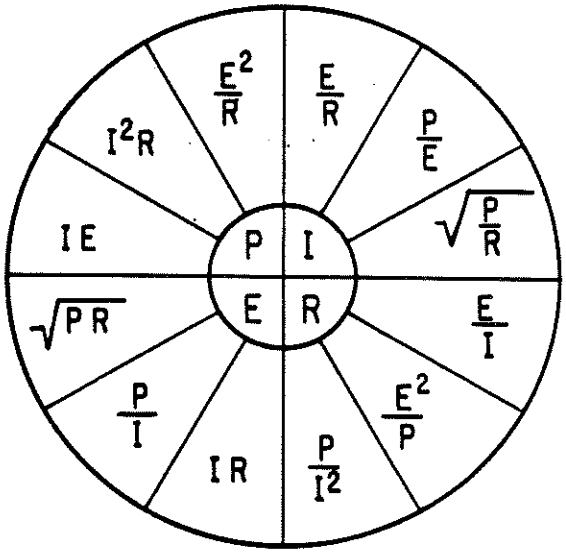


Figure 3-10.—Summary of basic formulas.

Electric soldering irons are of various wattage ratings, with the high-wattage irons changing more electrical energy to heat than those of low-wattage ratings.

If the normal wattage rating is exceeded, the equipment or device will overheat and probably be damaged. For example, if a lamp is rated 100 watts at 110 volts and is connected to a source of 220 volts, the current through the lamp will double. This will cause the lamp to use four times the wattage for which it is rated, and it will burn out quickly.

POWER CAPACITY OF ELECTRICAL DEVICES

Rather than indicate a device's ability to do work, its wattage rating may indicate the de-

vice's operating limits. These power limits generally are given as the maximum or minimum safe voltages and currents to which a device may be subjected. However, in cases where a device is not limited to any specific operating voltage, its limits are given directly in watts.

Resistors

A resistor is an example of such a device. It may be used in circuits with widely different voltages, depending on the desired current. However, the resistor has a maximum current limitation for each voltage applied to it. The product of the resistor's voltage and current at any time must not exceed a certain wattage.

Thus, resistors are rated in watts, in addition to their ohmic resistance. Resistors of the same resistance value are available in different wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/3, 1/2, 1, and 2 watts. The larger the physical size of a carbon resistor, the higher its wattage rating, since a larger amount of material will absorb and give up heat more easily.

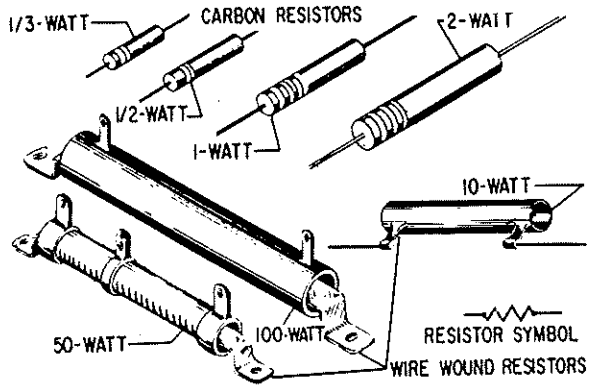


Figure 3-11.–Resistors of different wattage ratings.

When resistors of wattage ratings greater than 2 watts are needed, wire-wound resistors are used. Such resistors are made in ranges between 5 and 200 watts, with special types being used for power in excess of 200 watts.

Fuses

When current passes through a resistor, electric energy is transformed into heat, which raises the temperature of the resistor. If the temperature becomes too high, the resistor may be damaged. The metal wire in a wound resistor may melt, opening the circuit and interrupting current flow. This effect is used to an advantage in fuses.

Fuses are actually metal resistors with very low resistance values. They are designed to "blow out" and thus open a circuit when current exceeds the fuse's rated value.

When the power consumed by the fuse raises the temperature of its metal too high, the metal melts, or "blows." In service, fuses are generally connected as shown in figure 3-12.

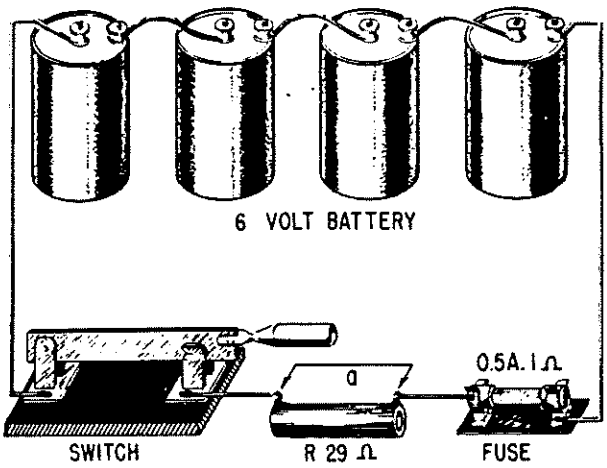


Figure 3-12.–Simple fused circuit.

Note that all current flowing through the load resistance of 29 ohms must also flow through the half-ampere fuse. Under normal conditions, the total resistance would be 29 + 1 = 30 ohms. If the switch were closed, the current I would be

$$I = \frac{E}{R}$$

$$I = \frac{6}{30}$$

$$I = 0.2 \text{ ampere}$$

This would be less than the rated current of the fuse, and it would not open. However, if the short conductor (a, fig. 3-12) were connected, the load resistance would be bypassed, or "shorted out." Only the fuse resistance of one ohm would remain in the circuit. Current would

then be

$$I = \frac{E}{R}$$

$$I = \frac{6}{1}$$

$$I = 6 \text{ amperes}$$

Six amperes of current will cause the half-ampere fuse to open very quickly, because its wattage rating is greatly exceeded.

There are a great number of different types and sizes of fuses presently in use. Figure 3-13 shows three of the most common types.

ENERGY

Energy is defined as the ability to do work. Energy is expended when work is done, because

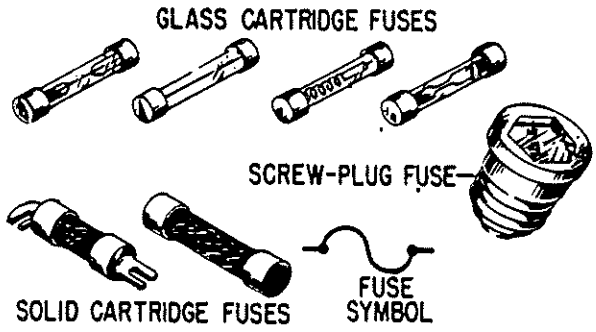


Figure 3-13.—Typical fuse types.

it takes energy to maintain a force when that force acts through a distance (works). The total energy expended to do a certain amount of work is equal to the working force multiplied by the distance through which the force moved to do the work. This is the mechanical definition.

In electricity, total energy expended is equal to the rate at which work is done, multiplied by the length of time the rate is measured. Essentially, energy W is equal to power P times time t.

Electrical energy is bought and sold in units of kilowatt-hours ($3{,}600 \times 10^3$ joules), and is totalized in large central generating stations in terms of megawatt-hours ($3{,}600 \times 10^6$ joules). For example, if the average demand over a 10-hour period is 70 megawatts, the total energy delivered is 70 x 10, or 700 megawatt-hours. This amount of energy is equivalent to 700 x 1,000 = 700,000 kilowatt-hours.

Problems

Ohm's law for power calculations may be applied to a great many everyday problems wherever electricity is at work.

Consider one of the most common examples —that of the incandescent electric light. Incandescent lamps for use in constant-potential circuits in homes and factories are rated in volts and watts. How much current do they take? How much resistance do they possess? If high powered, they may draw several amperes; if low in wattage rating, they may take only a small fraction of an ampere. Specifically the current rating of a 100-watt 120-volt lamp is easily found by transposing equation (3-2) and solving for the current. Thus

$$I = \frac{P}{E} = \frac{100}{120} = 0.833 \text{ ampere.}$$

The resistance of this lamp during normal operation may be found by substituting the calculated value of current and the rated voltage in equation (3-1) and transposing for R—

$$R = \frac{120}{0.833} = 144 \text{ ohms.}$$

Thus, a 100-watt 120-volt lamp draws a current of 0.833 ampere and has a hot resistance of 144 ohms. How much does it cost to use this lamp 4 hours each evening for 30 days at 3.2 cents per kilowatt-hour? Surprising little, as seen by the calculation:

$$\text{Total kilowatt-hours} = Pt = \frac{100 \times 4 \times 30}{1{,}000} = 12,$$

$$\text{Total cost} = 3.2 \times 12 = 38.4 \text{ cents.}$$

Consider the cost to operate a window air conditioner rated at 120 volts and 9.4 amperes in use 10 hours a day for 30 days. Applying equation (3-2), the power in kilowatts is

$$P = \frac{EI}{1{,}000} = \frac{120 \times 9.4}{1{,}000} = 1.128 \text{ kw.}$$

The total kilowatt-hours are 1.128 x 30 x 10, or 338.4 kw.-hr. At 3.2 cents per kw.-hr. the cost is \$0.032 x 338.4, or \$10.83.

QUIZ

1. In which direction does current flow in an electrical circuit?

   a. - to + externally, + to - internally
   b. + to - externally, + to - internally
   c. - to + externally, - to + internally
   d. + to - externally, - to + internally

2. Given the formula: $P = E^2/R$, solve for E.

   a. $E = \sqrt{ER}$ c. $E = IR$
   b. $E = \sqrt{PR}$ d. $E = \sqrt{P/R}$

3. Resistance in the power formula equals

   a. $R = \sqrt{I/P}$ c. $R = \sqrt{P \times I}$
   b. $R = E/I$ d. $R = E^2/P$

4. One joule is equal to
   a. 1 watt second
   b. 10 watt seconds
   c. 1 watt minute
   d. 10 watt minutes

5. A lamp has a source voltage of 110 v. and a current of 0.9 amps. What is the resistance of the lamp?
   a. 12.22 Ω c. 0.008 Ω
   b. 122.2 Ω d. 0.08 Ω

6. In accordance with Ohm's law, the relationship between current and voltage in a simple circuit is that the
   a. current varies inversely with the resistance if the voltage is held constant
   b. voltage varies as the square of the applied e.m.f.
   c. current varies directly with the applied voltage if the resistance is held constant
   d. voltage varies inversely as the current if the resistance is held constant

7. The current needed to operate a soldering iron which has a rating of 600 watts at 110 volts is
   a. 0.182 a. c. 18.200 a.
   b. 5.455 a. d. 66.000 a.

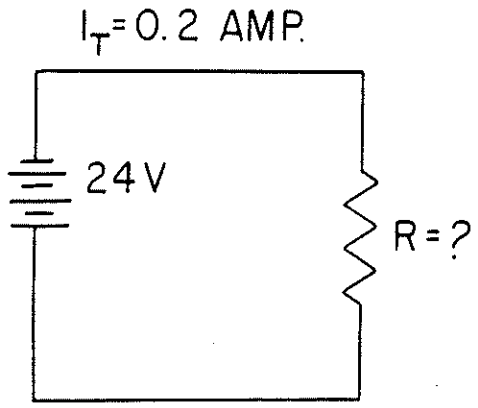
8. In electrical circuits, the time rate of doing work is expressed in
   a. volts c. watts
   b. amperes d. ohms

9. If the resistance is held constant, what is the relationship between power and voltage in a simple circuit?
   a. Resistance must be varied to show a true relationship
   b. Power will vary as the square of the applied voltage
   c. Voltage will vary inversely proportional to power
   d. Power will vary directly with voltage

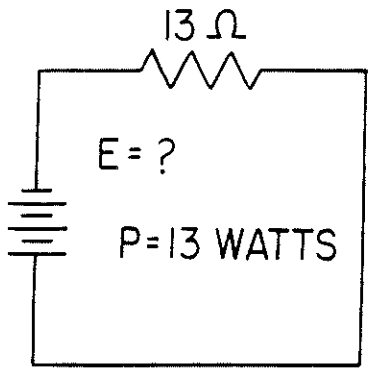
10. How many watts are there in 1 horsepower?
    a. 500 c. 746
    b. 640 d. 1,000

11. What formula is used to find watt-hours?
    a. E x T c. E x I x $\angle\theta$
    b. E x I x T d. E x I^2

12. What is the resistance of the circuit shown below?
    a. 4.8 Ω c. 48 Ω
    b. 12.0 Ω d. 120 Ω



13. In the figure below, solve for I_T
    a. 0.5 a. c. 13 a.
    b. 1 a. d. 169 a.



14. A simple circuit consists of one power source,
    a. and one power consuming device
    b. one power consuming device, and connecting wiring
    c. protective device, and control device
    d. one power consuming device, and protective device

15. The device used in circuits to prevent damage from overloads is called a
    a. fuse
    b. switch
    c. resistor
    d. connector

16. What happens in a series circuit when the voltage remains constant and the resistance increases?
    a. Current increases
    b. Current decreases
    c. Current remains the same
    d. Current increases by the square

17. Other factors remaining constant, what would be the effect on the current flow in a given circuit if the applied potential were doubled?
    a. It would double
    b. It would remain the same
    c. It would be divided by two
    d. It would be divided by four

18. Which of the following procedures can be used to calculate the resistance of a load?
    a. Multiply the voltage across the load by the square of the current through the load
    b. Divide the current through the load by the voltage across the load
    c. Multiply the voltage across the load by the current through the load
    d. Divide the voltage across the load by the current through the load

19. A cockpit light operates from a 24-volt d-c supply and uses 72 watts of power. The current flowing through the bulb is
    a. 0.33 amps
    b. 3 amps
    c. 600 amps
    d. 1,728 amps

20. If the resistance is held constant, what happens to power if the current is doubled?
    a. Power is doubled
    b. Power is multiplied by 4
    c. Power is halved
    d. Power is divided by 4

CHAPTER 4

DIRECT-CURRENT SERIES AND PARALLEL CIRCUITS

An electric circuit is a complete path through which electrons can flow from the negative terminal of the voltage source; through the connecting wires, or conductors; through the load, or loads; and back to the positive terminal of the voltage source. A circuit is thus made up of a voltage source, the necessary connecting conductors, and the effective load.

If the circuit is arranged so that the electrons have only ONE possible path, the circuit is called a SERIES CIRCUIT. If there are two or more paths supplied by a common voltage source, the circuit is called a PARALLEL CIRCUIT.

In any type of work that utilizes the effects of electron flow a knowledge of series and parallel circuits is desirable. None of the effects accompanying electron flow—for example, heating, lighting, or magnetic effects—would be possible without the use of electric circuits; and many electrical devices can be utilized more effectively if the operator has a knowledge of how they work. The purpose of this chapter is to give in simplified form conventional methods of calculating resistance in basic series and parallel circuits and to show how problems involving current, voltage, and power may be solved by the use of basic formulas.

Series Circuits

KIRCHHOFF'S VOLTAGE LAW APPLIED TO SERIES CIRCUITS

All conductors have resistance, and therefore a circuit made up of nothing but conductors would have some resistance, however small it might be. In circuits containing long conductors through which an appreciable amount of current is drawn the resistance of the conductors becomes important. However, for the purposes of this chapter the resistance of the connecting wires is neglected, and only the resistance of each resistor element (which may be any device that has resistance) is considered.

Kirchhoff's Law of Voltages states that the algebraic sum of all the voltages in any complete electric circuit is equal to zero. In other words, the sum of all positive voltages MUST BE equal to the sum of all negative voltages. For any voltage rise there must be an equal voltage drop somewhere in the circuit. The voltage rise (potential source) is usually regarded as the power supply, such as a battery. The voltage drop is usually regarded as the load, such as a resistor. The voltage drop may be distributed across a number of resistive elements, such as a string of lamps or several resistors. However, according to Kirchhoff's Law, the sum of their individual voltage drops MUST ALWAYS equal the voltage rise supplied by the power source.

The statement of Kirchhoff's Law can be translated into a truthful equation, from which many unknown circuit factors may be determined. (Refer to fig. 4-1.) Note that the source voltage E_S is equal to the sum of the three load voltages E_1, E_2, and E_3. In a formula, this would be written

$$E_s = E_1 + E_2 + E_3.$$

This formula may also be transposed to demonstrate that the algebraic sum of all the voltages is zero, as follows:

$$E_s - E_1 - E_2 - E_3 = 0.$$

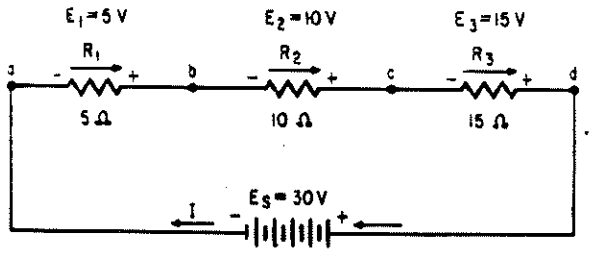


Figure 4-1.—Series circuit for demonstrating Kirchhoff's Voltage Law.

In order to solve problems applicable to figure 4-1, and others similar to it, the following procedure is suggested.

1. Note the polarity of the source e.m.f. (E_S) and indicate the electron flow around the circuit. Electron flow is out from the negative terminal of the source, through the load, and back to the positive terminal of the source. In the example being considered, the arrows indicate electron flow in a clockwise direction around the circuit.

2. To apply Kirchhoff's Law it is necessary to establish a voltage equation. The equation is developed by tracing around the circuit and noting the voltage absorbed (called voltage drop) across each part of the circuit encountered by the trace, and expressing the sum of these voltages according to the voltage law. It is important that the trace be made around a closed circuit, and that it encircle the circuit only once. Thus, a point is arbitrarily selected at which to start the trace. The trace is then made, and upon completion, the terminal point coincides with the starting point.

3. Sources of e.m.f. are preceded by a PLUS sign if in tracing through the source the first terminal encountered is positive; if the first terminal is negative, the e.m.f. is preceded by a MINUS sign.

4. Voltage drops along wires and across resistors (loads) are preceded by a minus sign if the trace is in the assumed direction of electron flow; if in the opposite direction the sign is plus.

5. If the assumed direction of electron flow is incorrect, the error will be indicated by a minus sign preceding the current, in solving for circuit current. The magnitude of the current will not be affected.

The preceding rules may be applied to the example of figure 4-1 as follows:

1. The left terminal of the battery is negative, the right terminal is positive, and electron flow is clockwise around the circuit.

2. The trace may arbitrarily be started at the positive terminal of the source and continued clockwise through the source to its negative terminal. From this point the trace is continued around the circuit to a, b, c, d, and back to the positive terminal, thus completing the trace once around the entire closed circuit.

3. The first term of the voltage equation is $+ E_S$.

4. The second, third, and fourth terms are respectively, $- E_1$, $- E_2$, and $- E_3$. Their algebraic sum is equated to zero as follows:

$$E_s - E_1 - E_2 - E_3 = 0.$$

Transposing the voltage equation and solving for E_S,

$$E_s = E_1 + E_2 + E_3.$$

Since $E = IR$ from Ohm's law, the voltage drop across each resistor may be expressed in terms of the current and resistance of the individual resistor as follows:

$$E_s = IR_1 + IR_2 + IR_3,$$

where R_1, R_2, and $R3$ are the resistances, E_S is the source voltage, and I is the circuit current.

E_S may be expressed in terms of the circuit current and total resistance as IR_t. Substituting IR_t for E_S, the voltage equation becomes,

$$IR_t = IR_1 + IR_2 + IR_3.$$

Since there is only one path for current in the series circuit, the total current is the same in all parts of the circuit. Dividing both sides of the voltage equation by the common factor, I, an expression is derived for the total resistance of the circuit.

$$R_t = R_1 + R_2 + R_3.$$

Therefore, in series circuits THE TOTAL RESISTANCE IS THE SUM OF THE RESISTANCES OF THE INDIVIDUAL PARTS OF THE CIRCUIT.

In the example of figure 4-1, the total resistance is

$$5 + 10 + 15 = 30 \text{ ohms.}$$

The total current may be found by applying the equation

$$I_t = \frac{E_t}{R_t} = \frac{30}{30} = 1 \text{ ampere.}$$

The power absorbed by resistor R_1 is I^2R_1, or 1^2 x 5 = 5 watts. Similarly the power absorbed by R_2 is 1^2 x 10 = 10 watts, and the power absorbed by R_3 is 1^2 x 15 = 15 watts. The total power absorbed is the arithmetic sum of the power of each resistor, or 5 + 10 + 15 = 30 watts. The value is also calculated by $P_t = E_tI_t$ = 30 x 1 = 30 watts.

More than one voltage source may be used in a series circuit. If the polarities of the sources are such that they aid each other, they are simply added together, and the net result is the same as if a single source of higher voltage had been used. If the polarities of the sources are such that one or more of them tend to cancel or "buck out" the effect of the others, then the net result is the difference between the source voltages that would cause the circuit current to flow in one direction and the source voltages that cause it to flow in the opposite direction.

Actually, the current could be assumed to flow in either direction as long as the minus sign is placed before each voltage drop (when the circuit is traced in the direction of the assumed current flow) and the proper sign (the one encountered as the source is approached in the circuit) is placed before all voltage sources. As mentioned previously, if the resultant circuit current has a negative sign it merely means that the assumed direction of current flow is incorrect.

Kirchhoff's Voltage Law is readily applied in solving series circuit problems. In many cases, it is the most practical method that may be used. For example, in figure 4-2, Kirchhoff's Voltage Law is used to solve for current, I; and when this has been determined, the other unknown values may be determined by Ohm's Law or the associated power formulas.

In figure 4-2 (A), the two voltage sources are aiding each other; that is, the polarities are connected so that each source tends to make the current flow clockwise around the circuit. Starting at the left terminal of $R1$ and proceeding clockwise around the circuit, the voltage equation is,

$$-E_1 - E_2 + E_{s2} - E_3 - E_4 - E_5 - E_6 + E_{s1} = 0.$$

Expressing the voltage drops around the circuit in terms of current and resistance, and the given values of source voltage, the equation becomes,

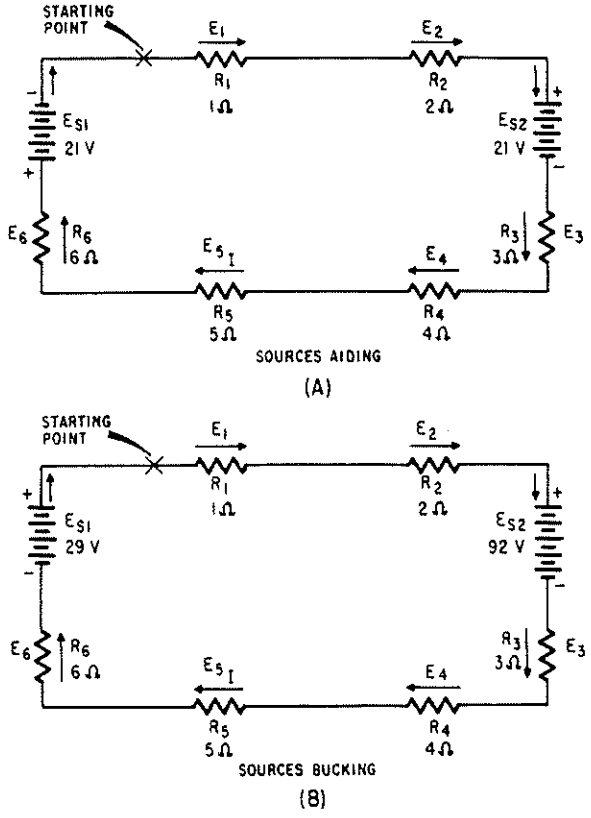


Figure 4-2.—Application of Kirchhoff's Law to series circuits.

$$-I - 2I + 21 - 3I - 4I - 5I - 6I + 21 = 0,$$
$$-21I + 42 = 0,$$
$$42 = 21I,$$
$$I = 2 \text{ amperes.}$$

I is positive and therefore the assumed direction of current flow is correct. (In this case the direction of current flow was obvious.)

The total power absorbed by the resistors in figure 4-2 (A), is the sum of the power absorbed by each resistor.

The power in $R1$ is $I^2R_1 = 2^2$ x 1 = 4 watts.
The power in $R2$ is $I^2R_2 = 2^2$ x 2 = 8 watts.
The power in $R3$ is $I^2R_3 = 2^2$ x 3 = 12 watts.
The power in $R4$ is $I^2R_4 = 2^2$ x 4 = 16 watts.
The power in $R5$ is $I^2R_5 = 2^2$ x 5 = 20 watts.
The power in $R6$ is $I^2R_6 = 2^2$ x 6 = 24 watts.

Note that in the above calculations for power the current values in each is the same because these calculations apply to a series circuit. The total power absorbed is

$$4 + 8 + 12 + 16 + 20 + 24 = 84 \text{ watts.}$$

A check on the calculation is that the total power absorbed is equal to $I_t E_t$, or

$$2 \times (21 + 21) = 84 \text{ watts.}$$

In figure 4-2 (B), the voltage sources are bucking. Because E_{S2} is larger then E_{S1}, E_S2 determines the direction of current flow, and this direction is clockwise around the circuit. Starting at the left terminal of $R1$ and proceeding clockwise around the circuit, the voltage equation is,

$$-E_1 - E_2 + E_{s2} - E_3 - E_4 - E_5 - E_6 - E_{s1} = 0,$$

or

$$-I - 2I + 92 - 3I - 4I - 5I - 6I - 29 = 0,$$

from which

$$I = \frac{92 - 29}{21} = 3 \text{ amperes.}$$

The power absorbed by $R1$ is $I^2R_1 = 3^2 \times 1 = 9$ watts.
The power absorbed by $R2$ is $I^2R_2 = 3^2 \times 2 = 18$ watts.
The power absorbed by $R3$ is $I^2R_3 = 3^2 \times 3 = 27$ watts.
The power absorbed by $R4$ is $I^2R_4 = 3^2 \times 4 = 36$ watts.
The power absorbed by $R5$ is $I^2R_5 = 3^2 \times 5 = 45$ watts.
The power absorbed by $R6$ is $I^2R_6 = 3^2 \times 6 = 54$ watts.
The total power is

$$9 + 18 + 27 + 36 + 45 + 54 = 189 \text{ watts.}$$

A check on the calculation is that the total power absorbed is equal to the product of the net voltage, acting in the direction of electron flow, and the current, or

$$EI = (92 - 29) \times 3 = 189 \text{ watts.}$$

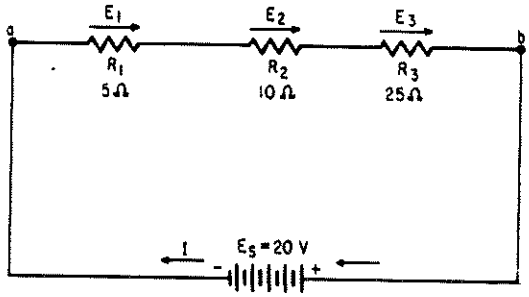
TYPICAL PROBLEMS IN SERIES CIRCUITS

As seen by the preceding calculations, problems involving the determination of resistance, voltage, current, and power in a series circuit are relatively simple. It is necessary only to draw or visualize the circuit, to list the known values, and to determine by means of Ohm's Law (or Kirchhoff's adaptation of Ohm's Law) the unknown values.

In figure 4-3 (A), it is desired to find the total resistance, R_t, the current, I, and the voltage drops across $R1$, $R2$, and $R3$.

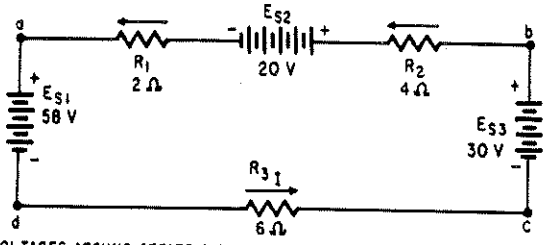
The total resistance is equal to the sum of the individual resistors. Thus,

$$R_t = R_1 + R_2 + R_3 = 5 + 10 + 25 = 40\,\Omega.$$



VOLTAGE AROUND SERIES CIRCUIT HAVING ONE VOLTAGE SOURCE

(A)



VOLTAGES AROUND SERIES CIRCUIT HAVING VOLTAGE SOURCES IN OPPOSITION

(B)

Figure 4-3.—Solving for R_t, E, and I in series circuits.

The current is

$$I = \frac{E_s}{R_t} = \frac{20}{40} = 0.5 \text{ ampere.}$$

The current is the same in all parts of the series circuit, and therefore the same current flows through $R1$, $R2$, and $R3$. The voltage drops across $R1$, $R2$, and $R3$ are indicated as

$$E_1 = I \times R_1 = 0.5 \times 5 = 2.5 \text{ volts,}$$

$$E_2 = I \times R_2 = 0.5 \times 10 = 5 \text{ volts,}$$

and

$$E_3 = I \times R_3 = 0.5 \times 25 = 12.5 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the individual voltage drops is equal to the source voltage, or

$$E_s = E_1 + E_2 + E_3 = 2.5 + 5 + 12.5 = 20 \text{ volts.}$$

The power absorbed by $R1$ is $\frac{E_1^2}{R_1} = \frac{(2.5)^2}{5} =$ 1.25 watts.

The power absorbed by $R2$ is $\frac{E_2^2}{R_2} = \frac{5^2}{10} =$ 2.50 watts.

The power absorbed by $R3$ is $\frac{E_3^2}{R_3} = \frac{(12.5)^2}{25} =$ 6.25 watts.

The total power absorbed by the 3 resistors is 1.25 + 2.5 + 6.25, or 10 watts. This value may be checked by the equation,

$$P_t = E_t I_t = 20 \times 0.5 = 10 \text{ watts.}$$

In the example of figure 4-3 (B), the circuit trace is arbitrarily started at point a and continued in a clockwise direction completely around the circuit and back to point a. The voltage equation is written in terms of both (1) known voltages and (2) current and resistance. The equation is solved for current in terms of voltage and resistance. The three voltage sources are arranged so that E_{S1} and E_{S2} are additive and both are opposed to E_{S3}. Since the sum of E_{S1} and E_{S2} is greater than E_{S3} the electron flow is determined by E_{S1} and E_{S2} and is seen to be in a counterclockwise direction around the circuit as indicated by the arrows above the resistors.

Representing the unknown current as I, the voltage equation is,

$$2I - 20 + 4I + 30 + 6I - 58 = 0$$

$$12I - 48 = 0$$

$$I = \frac{48}{12} = 4 \text{ amperes.}$$

The voltage drop across $R1$ is $IR_1 = 4 \times 2 =$ 8 volts.

The voltage drop across $R2$ is $IR_2 = 4 \times 4 =$ 16 volts.

The voltage drop across $R3$ is $IR_3 = 4 \times 6 =$ 24 volts.

The total voltage acting in the direction of electron flow is equal to

$$8 + 16 + 24, \text{ or } 48 \text{ volts.}$$

The power absorbed in $R1$ is $I^2R_1 = 4^2 \times 2 =$ 32 watts.

The power absorbed in $R2$ is $I^2R_2 = 4^2 \times 4 =$ 64 watts.

The power absorbed in $R3$ is $I^2R_3 = 4^2 \times 6 =$ 96 watts.

The total power absorbed by the three resistors is

$$32 + 64 + 96 = 192 \text{ watts.}$$

The calculation may be checked by the relation

$$P_t = E_t I = 48 \times 4 = 192 \text{ watts.}$$

The filaments of light bulbs and electron tubes are made of materials that have appreciable resistance. Most incandescent lamps have tungsten filaments. The heat produced by the current flowing through the resistance of the filament is intense enough to make the tungsten wires white hot and thus produce artificial light. Radio receivers of the common a-c/d-c variety have their filaments connected in series, as shown in figure 4-4. The tube designations are shown directly above the filament symbols, $R1$, $R2$, and so forth. The first two numerals in the designation indicate the approximate voltage that must be applied to the filament to cause rated current to flow. For example, 12 volts must be applied to the filament of the 12SA7 tube to cause the rated current of 0.15 ampere to flow.

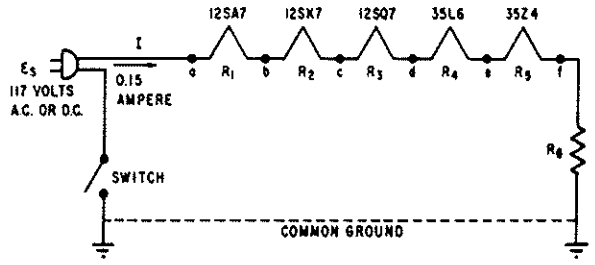


Figure 4-4.—Typical series circuit.

The first problem is to find the value of $R6$ that will cause 0.15 ampere to flow in the circuit when the applied voltage is 117 volts. By observation it is seen that the tube filaments will absorb

$$12 + 12 + 12 + 35 + 35 = 106 \text{ volts.}$$

Therefore, $R6$ must absorb the difference, or

$$117 - 106 = 11 \text{ volts.}$$

The resistance of $R6$ is,

$$R6 = \frac{E_6}{I} = \frac{11}{0.15} = 73.3 \text{ ohms.}$$

The power, P_6, absorbed by $R6$ is

$$P_6 = E_6 \times I = 11 \times 0.15 = 1.65 \text{ watts.}$$

The power absorbed by the 12SA7 filament is

$$P_1 = E_1 I = 12 \times 0.15 = 1.8 \text{ watts.}$$

The power absorbed by the 12SK7 and the 12SQ7 filaments is also 1.8 watts each, since they both have equal voltages and the same value of current. The 35L6 filament absorbs an amount of power equal to 35 x 0.15 = 5.25 watts and the 35Z4 filament absorbs an equal amount of power. The total power absorbed by the entire filament circuit is equal to the sum of the power absorbed by each separate unit. Thus,

$$P_t = 1.8 + 1.8 + 1.8 + 5.25 + 5.25 + 1.65 = 17.55 \text{ watts.}$$

The total power may be checked as follows:

$$P_t = E_t I = 117 \times 0.15 = 17.55 \text{ watts.}$$

In the foregoing examples of series circuits, an important relation should be pointed out. Note that the voltage dropped across each resistor is in proportion to its resistance. This fact is important and should be thoroughly understood. It is explained as follows:

When the power switch in a series circuit is closed, current through the circuit rises very rapidly. As the current increases from zero, the total voltage drop across the load also increases until it exactly equals the source voltage, at which time the current stabilizes at a steady flow. In this natural state of balance, the voltage absorbed by each ohm of resistance will depend on two things, (1) how many source volts must be absorbed, and (2) how many ohms there are in the circuit to absorb them. The voltage that each ohm of resistance must absorb is determined by dividing the total voltage by the total number of ohms. Thereafter, when the circuit is closed, current will rise until each ohm of resistance is absorbing, or dropping, a voltage that is maximum in value, and equal to all the others. Current will stabilize when the sum of all the ohmic drops equals the source, or impressed voltage. This is Kirchhoff's Voltage Law in action. Because the voltage-per-ohm and the series current vary directly and simultaneously, they must therefore be equal. For instance, when there are 10 amperes of current through one ohm of resistance, the voltage absorbed by that one ohm is 10 volts. Thus, the division of total voltage by the total number of ohms yields TWO values, (1) the voltage absorbed per ohm, and (2) the total current.

The Ohm's Law Formula $\frac{E}{R} = I$ is most often used to express this relation. It could also be written $\frac{E}{R} = e$, where e is the volts-per-ohm value for a series circuit, because e and I are interchangeable. The voltage absorbed by any particular resistor is equal to the voltage-per-ohm value for the circuit, multiplied by the number of ohms in the particular resistor. This relation could thus be written $E = eR$. In practice, however, I is most often substituted for e, and the relation becomes $E = IR$. Hence, the commonly-used term "IR drop."

The voltages around the series circuit shown in figure 4-4 are distributed in proportion to the resistances around the circuit. Thus, the voltage between any point, for example, ground, and some other point such as a, b, or c may be determined. For example, the potential from a to ground is the full 117 volts because the entire circuit is included. From b to ground, the potential is 117 volts less the drop of 12 volts across $R1$, or 105 volts, because the circuit includes everything except $R1$. The potential between point f and ground is 11 volts because $R6$ alone is included in this part of the circuit.

In this type of circuit, when an open occurs in any of the filaments or in $R6$, the current ceases to flow. However, the input current increases if any of the points, a, b, c, and so forth, should become grounded. For example, if point f should become grounded the resistance of $R6$ is no longer in the circuit, and 117 volts is applied between points a and f instead of 106 volts. The total filament current is increased to

$$\frac{117}{106} \times 0.15 = 0.165 \text{ ampere.}$$

The increase in current is proportioned to the increase in voltage. Over-voltage may cause the filament to overheat because of excessive current. Thus, the entire filament circuit will be deenergized when the circuit opens at some point due to filament burnout.

Effect of Source Resistance on Voltage, Power, and Efficiency

All sources of e.m.f. have some internal resistance that acts in series with the load resistance. The source resistance is generally indicated in circuit diagrams as a separate resistor connected in series with the source. Both the voltage and power made available to the load may be increased if the resistance of the source is reduced.

The effects of source resistance, R_S, on load voltage may be illustrated by the use of figure 4-5. In figure 4-5 (A), the circuit is open, and therefore a voltmeter connected across the battery will read the open-circuit voltage. In the case of a dry cell, the open-circuit voltage is 1.5 volts. In figure 4-5 (B), the cell is short-circuited through the ammeter, and a current of 30 amperes flows from the source. In this case the voltage of the cell is developed across the internal resistance of the cell. The internal resistance of the cell is therefore,

$$R_s = \frac{E_s}{I} = \frac{1.5}{30} = 0.05 \text{ ohm.}$$

If a load, R_L, of 0.10 ohm is connected to the circuit, as shown in figure 4-5 (C), the current, I, becomes

$$I = \frac{E_s}{R_t} = \frac{1.5}{0.15} = 10 \text{ amperes.}$$

The voltage available at the load is

$$E_L = IR_L = 10 \times 0.1 = 1 \text{ volt.}$$

The voltage absorbed across the internal resistance of the cell is

$$IR_s = 10 \times 0.05 = 0.5 \text{ volt.}$$

Thus the effect of the internal resistance is to decrease the terminal voltage from 1.5 volts to 1 volt when the cell delivers 10 amperes to the load.

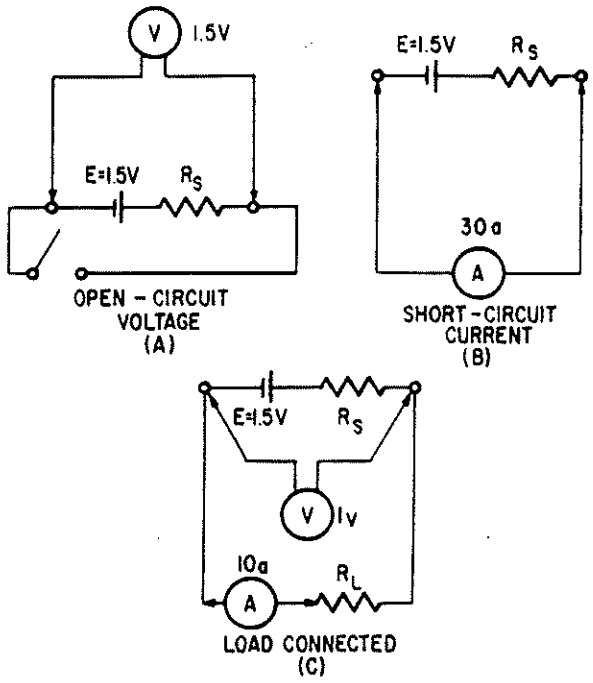


Figure 4-5.—Effect of source resistance on load voltage.

Parallel Circuits

OHM'S LAW APPLIED TO PARALLEL CIRCUITS

In the parallel circuit, each load (or branch), is connected directly across the voltage source, as shown in figure 4-7. As a result, there are as many separate paths for current flow as there are branches. When additional loads were added in the series circuit, total resistance was increased and total current decreased. In the parallel circuit, just the opposite is true. As loads are added in parallel, they simply become additional paths for current flow, and therefore the total current supplied by the source increases as they are added. If total current is increased, total resistance must have been decreased. Therefore, as branches are added in parallel, regardless of their resistances, the total resistance as seen from the voltage source DECREASES.

The voltage across all branches of a parallel circuit is the same, because all branches are connected directly to the voltage source. Consequently, the current through each branch is independent of the others, and depends only on the resistance of the particular branch, at a given voltage. The current through each branch may thus be computed separately, simply by dividing its resistance into the source voltage. The branch currents in figure 4-7 are:

$$I_1 = \frac{E_s}{R_1} = \frac{30}{5} = 6 \text{ amperes,}$$

$$I_2 = \frac{E_s}{R_2} = \frac{30}{10} = 3 \text{ amperes,}$$

and

$$I_3 = \frac{E_s}{R_3} = \frac{30}{30} = 1 \text{ ampere.}$$

The total current, I_t, of the parallel circuit is equal to the sum of the currents through the individual branches. This, in slightly different words, is Kirchhoff's current law, which is treated later in this chapter. In this case, the total current is

$$I_t = I_1 + I_2 + I_3 = 6 + 3 + 1 = 10 \text{ amperes.}$$

In order to find the equivalent, or total resistance, R_t (for simplicity, R_t is used instead of R_{eq}), of the combination shown in figure 4-7, Ohm's law is first used to find each of the

currents (I_t, I_1, I_2, and I_3). Substituting the Ohm's Law equivalent for current ($\frac{E}{R}$) in the current equation, that equation ($I_t = I_1 + I_2 + I_3$) becomes

$$\frac{E_s}{R_t} = \frac{E_s}{R_1} + \frac{E_s}{R_2} + \frac{E_s}{R_3}$$

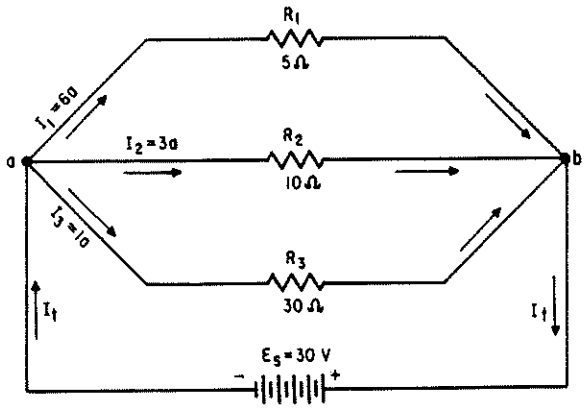


Figure 4-7.—Resistors in parallel.

This introduces the factor R_t into the equation, which is the quantity you are attempting to determine. Since E_S appears as the numerator in all four factors, it is divided out, and the equation then contains only the desired factor R_t:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3},$$

$$= \frac{1}{5} + \frac{1}{10} + \frac{1}{30},$$

$$= 0.2 + 0.1 + 0.033,$$

$$\frac{1}{R_t} = 0.333,$$

$$R_t = \frac{1}{0.333},$$

$$= 3 \text{ ohms (approx.)}.$$

A useful rule to remember in computing the equivalent resistance of a d-c parallel circuit is that THE TOTAL RESISTANCE IS ALWAYS LESS THAN THE SMALLEST RESISTANCE IN ANY OF THE BRANCHES.

There are two shortcuts that may be used in solving for the equivalent resistance of a parallel circuit.

The first applies only to any number of parallel resistors all of which have THE SAME VALUE OF RESISTANCE. The equivalent resistance is determined by dividing the resistance of one resistor by the number of resistors in parallel. Thus, the equivalent resistance of five 10-ohm resistors connected in parallel is

$$R_t = \frac{10}{5} = 2 \text{ ohms.}$$

The second shortcut applies when two and only two resistors of different values are connected in parallel. The equivalent resistance is equal to their product divided by their sum. For example, if two resistors having resistances of 3 ohms and 6 ohms are connected in parallel, the equivalent resistance is

$$R_t = \frac{R_1 R_2}{R_1 + R_2} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms.}$$

In addition to adding the individual branch currents to obtain the total current in a parallel circuit, the total current may be found directly by dividing the applied voltage by the equivalent resistance, R_t. For example, in figure 4-7

$$I_t = \frac{E_s}{R_t} = \frac{30}{3} = 10 \text{ amperes.}$$

The quantity $\frac{1}{R}$, as used in the foregoing equations, expresses CONDUCTANCE, whose standard symbol is G. When referring to the RESISTANCE of a circuit, you visualize the degree to which it RESISTS or PREVENTS current flow. When referring to its conductance, you visualize the degree to which the circuit PERMITS or CONDUCTS current flow. It is well to be able to work from either standpoint because some problems are easier to solve using circuit conductance instead of resistance, and vice versa.

The total conductance of a circuit is the reciprocal of its total resistance (the reciprocal

of any quantity is that quantity divided into one). Thus, the total conductance of a circuit is written

$$G_t = \frac{1}{R_t}$$

and

$$R_t = \frac{1}{G_t}$$

The term RELATIVE CONDUCTANCE applies to the comparison of two or more parallel branches. When two or more resistors are connected in parallel, each will conduct current in proportion to its resistance. To compare their relative conductances, each resistance is divided into the common numerator, 1. The larger a resistance the smaller its current flow, or relative conductance. The total conductance is the simple sum of all branch conductances:

$$G_t = G_1 + G_2 + G_3 + \cdots\cdots$$

or

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots\cdots$$

Since G and R are each an inversion of the other, as shown in equation (fig. 4-1), it follows that their Ohm's-Law equivalents are also inverted. That is, where R is expressed as $\frac{E}{I}$, G is expressed as $\frac{I}{E}$. Wherever R is used in Ohm's Law equations, the reciprocal of G may be used. For instance, where R is used as a multiplier in expressing E, $(E = IR)$, G would be used as a divisor, $(E = \frac{I}{G})$.

KIRCHHOFF'S CURRENT LAW APPLIED TO PARALLEL CIRCUITS

Kirchhoff's current law states that AT ANY JUNCTION OF CONDUCTORS THE ALGEBRAIC SUM OF THE CURRENTS IS ZERO. This is another way of saying that as many electrons must leave a junction as enter it. Consider junction a of figure 4-7. Assume that the current flowing toward junction a is positive and that the currents flowing away from the junction—that is, currents I_1, I_2, and I_3—are negative. Kirchhoff's current law is then expressed mathematically as

$$+I_t - I_1 - I_2 - I_3 = 0,$$

or

$$10 - 6 - 3 - 1 = 0.$$

As in the series circuit, the total power consumed in a parallel circuit is equal to the sum of the power consumed in the individual resistors. The power P_1, consumed in $R1$ of figure 4-7 is

$$P_1 = EI_1 = 30 \times 6 = 180 \text{ watts;}$$

the power, P_2, consumed in $R2$ is

$$P_2 = EI_2 = 30 \times 3 = 90 \text{ watts;}$$

and the power P_3, consumed in $R3$ is

$$P_3 = EI_3 = 30 \times 1 = 30 \text{ watts.}$$

The total power, P_t, consumed is the sum of the power consumed in the individual branch units—that is,

$$P_t = P_1 + P_2 + P_3 = 180 + 90 + 30 = 300 \text{ watts.}$$

The total power may be checked as

$$P_t = EI_t = 30 \times 10 = 300 \text{ watts.}$$

TYPICAL PROBLEMS IN PARALLEL CIRCUITS

Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is the same—(1) draw a circuit diagram, (2) state the values given and the values to be found, (3) state the applicable equations, and (4) substitute the given values and solve for the unknown.

For example, the parallel circuit of figure 4-8 consists of 2 branches (a and b). Branch a consists of 3 lamps in parallel. Their ratings are L_1 = 50 watts, L_2 = 25 watts, and L_3 = 75 watts. Branch b also has 3 lamps in parallel with ratings of L_4 = 150 watts, L_5 = 200 watts, and L_6 = 250 watts. The source voltage is 100 volts.

1. Find the current in each lamp.
2. Find the resistance of each lamp.
3. Find the current in branch a.

4. Find the current in branch *b*.
5. Find the total circuit current.
6. Find the total circuit resistance.
7. Find the total power supplied to the circuit.
8. Check 7 by a separate calculation.

1. The current in $L1$ is $I = \frac{P}{E} = \frac{50}{100} = 0.50$ ampere.

   The current in $L2$ is $\frac{25}{100} = 0.25$ ampere.

   The current in $L3$ is $\frac{75}{100} = 0.75$ ampere.

   The current in $L4$ is $\frac{150}{100} = 1.50$ amperes.

   The current in $L5$ is $\frac{200}{100} = 2.00$ amperes.

   The current in $L6$ is $\frac{250}{100} = 2.5$ amperes.

2. The resistance of $L1$ is $R = \frac{E}{I} = \frac{100}{0.5} = 200$ ohms.

   The resistance of $L2$ is $\frac{100}{0.25} = 400$ ohms.

   The resistance of $L3$ is $\frac{100}{0.75} = 133$ ohms.

   The resistance of $L4$ is $\frac{100}{1.5} = 66.7$ ohms.

   The resistance of $L5$ is $\frac{100}{2.0} = 50$ ohms.

   The resistance of $L6$ is $\frac{100}{2.5} = 40$ ohms.

3. The current in branch *a* is

$$I_1 + I_2 + I_3 = 0.5 + 0.25 + 0.75 = 1.5 \text{ amperes.}$$

4. The current in branch *b* is

$$I_4 + I_5 + I_6 = 1.5 + 2.0 + 2.5 = 6.0 \text{ amperes.}$$

5. The total circuit current is

$$I_a + I_b = 1.5 + 6.0 = 7.5 \text{ amperes.}$$

6. The total circuit resistance is

$$R_t = \frac{E}{I_t} = \frac{100}{7.5} = 13.3 \text{ ohms.}$$

7. The total power supplied to the circuit is

$$50 \text{ w.} + 25 \text{ w.} + 75 \text{ w.} + 150 \text{ w.} + 200 \text{ w.} + 250 \text{ w.} = 750 \text{ watts.}$$

8. The total power is also equal to

$$P_t = EI_t = 100 \times 7.5 = 750 \text{ watts.}$$

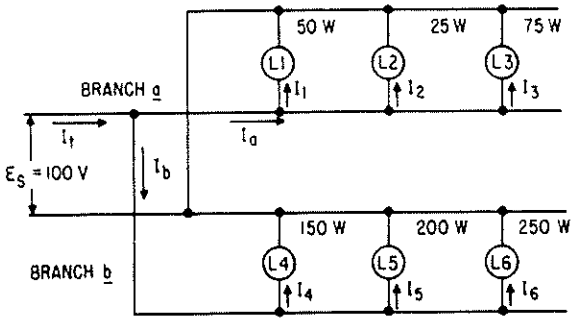


Figure 4-8.—Typical parallel circuit.

PRACTICAL APPLICATIONS OF SERIES AND PARALLEL CIRCUITS

One of the most common series circuits is the familiar string of Christmas tree lamps. When one of the lamps in the string burns out, all of the lamps go out because there is no longer a complete pathway through which the electrons can flow.

If the string is composed of 10 lamps of the same power rating and it is connected to a 120-volt source, 12 volts will be applied across each lamp. If one of the lamps burns out and the line is then shorted across the socket of the burned-out lamp, current will continue to flow through the remaining 9 lamps. However, the source voltage of 120 volts will be applied to the remaining lamps, and 13.3 volts will be developed across each lamp. The resultant increase in current flow may quickly burn out another lamp in the string.

Airport runway lamps and street lamps are other applications of series circuits. For these applications, constant-current variable-voltage sources are employed. Where long circuits like these are used, line losses are kept to a minimum by the use of high voltage and low current. When one of the lamps burns out, a device at the lamp automatically shorts out the defective lamp, thus allowing the others to continue to burn. At the variable-voltage source there is an automatic reduction in voltage when the current tends to increase so that the rise in current through the remaining lamps is checked and the circuit current remains approximately constant at the rated value.

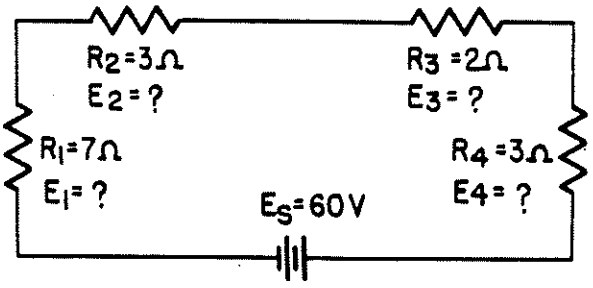
Most power and light distribution circuits are basically parallel circuits supplied by constant-potential variable-current sources.

Ship's service distribution systems are typical parallel circuits where many branch circuits are connected in parallel across the bus bars (the massive conductors that tie to the source).

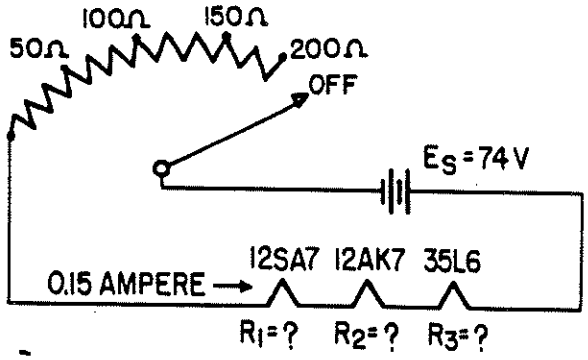
Distribution systems used in homes and factories are essentially networks of parallel circuits. The service conductors (the wires that bring the current to the home) are connected to the branch parallel circuits via a service switch and fuses. Each parallel circuit that is connected to the main circuit is likewise supplied with a fuse or circuit breaker of a lower current rating. On each individual branch circuit lamps or other loads are connected in parallel. Thus, in the home there are branch parallel circuits in parallel with other branch parallel circuits. Actually, nearly all the commonly encountered distribution electrical circuits are parallel circuits if the line resistance is disregarded.

QUIZ

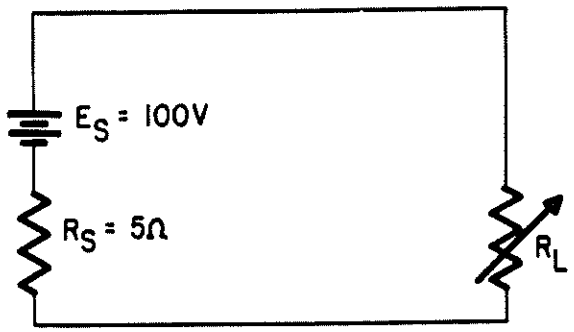
1. If a circuit is constructed so as to allow the electrons to follow only one possible path, the circuit is called a/an
   a. series-parallel circuit
   b. incomplete circuit
   c. series circuit
   d. parallel circuit
2. According to Kirchhoff's Law of Voltages, the algebraic sum of all the votages in a series circuit is equal to
   a. zero
   b. source voltage
   c. total voltage drop
   d. the sum of the IR drop of the circuit
3. In a series circuit, the total current is
   a. always equal to the source voltage
   b. determined by the load only
   c. the same through all parts of the circuit
   d. equal to zero at the positive side of the source
4. The correct voltage equation for the circuit below is
   a. $E_s + E_1 + E_2 + E_3 + E_4 = 0$
   b. $E_s - E_1 - E_2 - E_3 - E_4 = 0$
   c. $E_s = - E_1 - E_2 - E_3 - E_4$
   d. $- E_s = E_1 + E_2 + E_3 + E_4$



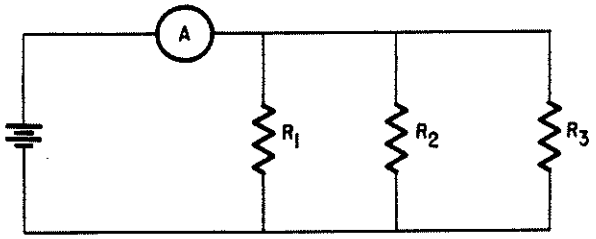
5. (Refer to the circuit used with question 4.) After expressing the voltage drops around the circuit in terms of current and resistance and the given values of source voltage, the equation becomes
   a. $-60 - 7I - 3I - 2I - 3I = 0$
   b. $-60 + 7I + 3I + 2I + 3I = 0$
   c. $60 - 7I - 3I - 2I - 3I = 0$
   d. $60 + 7I + 3I + 2I + 3I = 0$
6. By the use of the correct equation, it is found that the current (I) in the circuit used with question 4 is of positive value. This indicates that the
   a. assumed direction of current flow is correct
   b. assumed direction of current flow is incorrect
   c. problem is not solvable
   d. battery polarity should be reversed
7. In what position would the variable rheostat in the circuit below be placed in order that the filaments of the tubes operate properly with a current flow of 0.15 ampere?
   a. 50 Ω position
   b. 100 Ω position
   c. 150 Ω position
   d. 200 Ω position



8. The power absorbed by the variable rheostat in the circuit used with question 7, when placed in its proper operating position, would be
   a. 112.50 watts
   b. 2.25 watts
   c. 337.50 watts
   d. 450.00 watts
9. In the circuit below, maximum power would be transferred from the source to the load (R_L) if R_L were set at
   a. 2 ohms
   b. 5 ohms
   c. 12 ohms
   d. 24 ohms

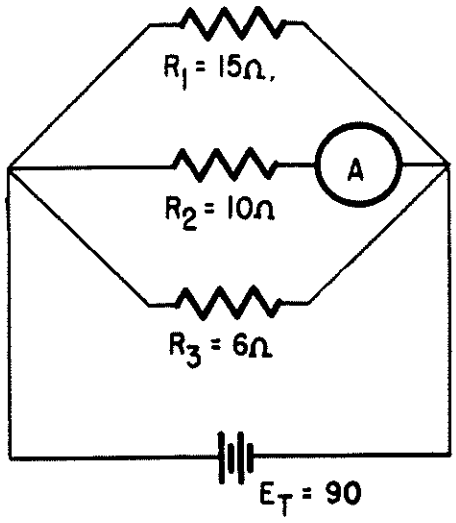


10. In the circuit below, if an additional resistor were placed in parallel to R_3 the ammeter reading would
    a. increase
    b. decrease
    c. remain the same
    d. drop to zero

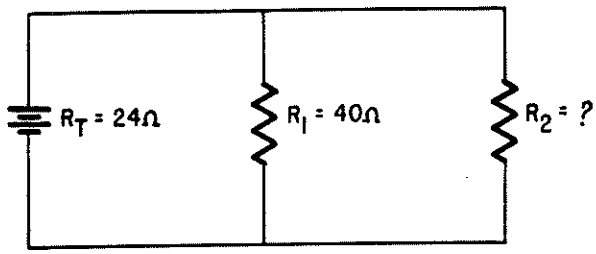


11. In a parallel circuit containing a 4-ohm, 5-ohm, and 6-ohm resistor, the current flow is
    a. highest through the 4-ohm resistor
    b. lowest through the 4-ohm resistor
    c. highest through the 6-ohm resistor
    d. equal through all three resistors
12. Three resistors of 2, 4, and 6 ohms, respectively, are connected in parallel. Which resistor would absorb the greatest power?
    a. The 2-ohm resistor
    b. The 4-ohm resistor
    c. The 6-ohm resistor
    d. It will be the same for all resistors
13. If three lamps are connected in parallel with a power source, connecting a fourth lamp in parallel will
    a. decrease E_T
    b. decrease I_T
    c. increase E_T
    d. increase I_T

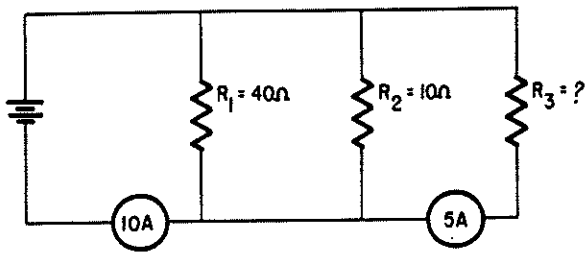
14. What is the current flow through the ammeter in the circuit shown below?
    a. 4 amps
    b. 9 amps
    c. 15 amps
    d. 28 amps



15. In the circuit shown below, the total resistance is 24 ohms. What is the value of R_2?
    a. 16 ohms
    b. 40 ohms
    c. 60 ohms
    d. 64 ohms

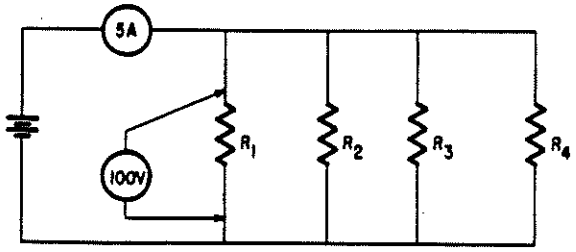


16. What is the source voltage of the circuit shown below?
    a. 40 volts
    b. 50 volts
    c. 100 volts
    d. 500 volts

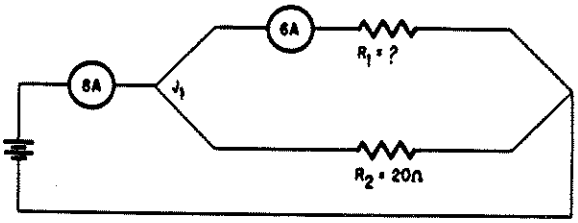


17. What is the value of R_3 in the circuit used with question 16?
    a. 8 ohms
    b. 10 ohms
    c. 20 ohms
    d. 100 ohms

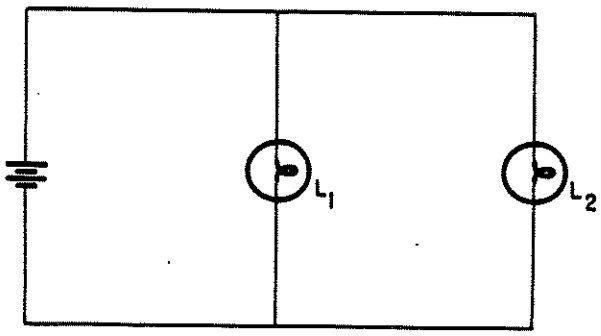
18. If all 4 resistors in the circuit below are of equal ohmic resistances, what is the value of R_3?
    a. 5 ohms
    b. 20 ohms
    c. 60 ohms
    d. 80 ohms



19. What is the value of the source voltage in the circuit below?
    a. 20 volts
    b. 40 volts
    c. 120 volts
    d. 160 volts

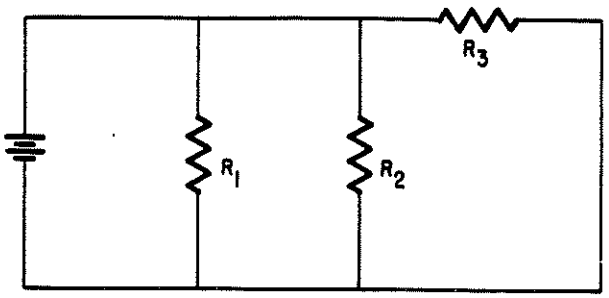


20. If lamp L_2 in the circuit below should suddenly burn out, which of the below statements is correct?
    a. More current would flow through lamp L_1
    b. Source voltage would decrease
    c. The filament resistance of lamp L_1 would decrease
    d. Lamp L_1 would still burn normal

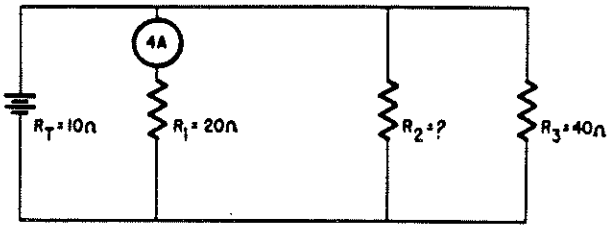


21. When referring to a circuit's conductance; you visualize the degree to which the circuit
    a. permits or conducts voltage
    b. opposes the rate of voltage changes
    c. permits or conducts current flow
    d. opposes the rate of current flow

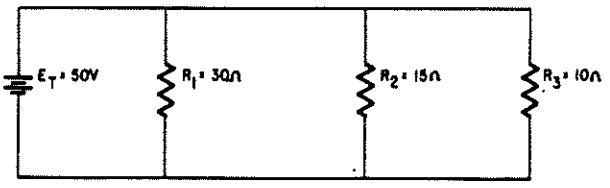
22. The total conductance of the circuit below would be solved by which of the equations?
    a. $G_T - G_1 - G_2 - G_3 = 0$
    b. $G_T + G_1 + G_2 + G_3 = 0$
    c. $G_T = G_1 - G_2 - G_3$
    d. $G_T = G_1 + G_2 + G_3$



23. If the resistors in the circuit below are all rated at 250 watts, which resistor or resistors would overheat?
    a. R_1
    b. R_2
    c. R_3
    d. All



24. The total conductance of the circuit below is
    a. 0.15 G
    b. 0.20 G
    c. 0.50 G
    d. 0.75 G



CHAPTER 5

DIRECT-CURRENT COMPOUND AND BRIDGE CIRCUITS

In the compound circuit, loads are connected in both series and parallel. For practical applications, you should become familiar with the compound circuit, since it is used more widely than any other type. You should be able to recognize and segregate the various combinations.

Series-Parallel Combinations

At least three resistors are required to form a compound circuit. Two basic series-parallel circuits are shown in figure 5-1. In figure 5-1 (A), $R1$ is connected in series with the parallel combination made up of $R2$ and $R3$.

The total resistance, R_t, of figure 5-1 (A), is determined in two steps. First, the resistance, $R_{2,3}$, of the parallel combination of $R2$ and $R3$ is determined as

$$R_{2,3} = \frac{R_2 R_3}{R_2 + R_3} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms.}$$

The sum of $R_{2,3}$ and R_1—that is, R_t—is

$$R_t = R_{2,3} + R_1 = 2 + 2 = 4 \text{ ohms.}$$

If the total resistance, R_t, and the source voltage, E_S, are known, the total current, I_t, may be determined by Ohm's law. Thus, in figure 5-1 (A),

$$I_t = \frac{E_s}{R_t} = \frac{20}{4} = 5 \text{ amperes.}$$

If the values of the various resistors and the current through them are known, the voltage drops across the resistors may be determined by Ohm's Law. Thus, in figure 5-1 (A),

$$E_{ab} = I_t R_1 = 5 \times 2 = 10 \text{ volts,}$$

and

$$E_{bc} = I_t R_{2,3} = 5 \times 2 = 10 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the voltage drops around the closed circuit is equal to the source voltage. Thus,

$$E_{ab} + E_{bc} = E_s,$$

or

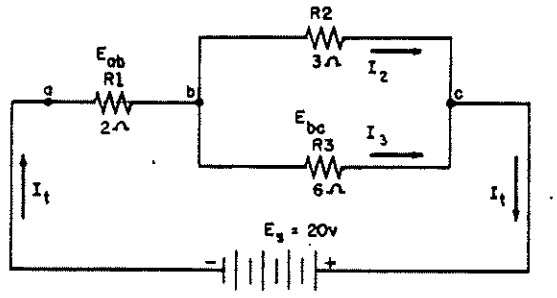
$$10 + 10 = 20 \text{ volts.}$$

If the voltage drop, E_{bc}, across $R_{2,3}$—that is, the drop between points b and c—is known, the current through the individual branches may be determined as

$$I_2 = \frac{E_{bc}}{R_2} = \frac{10}{3} = 3.333 \text{ amperes,}$$

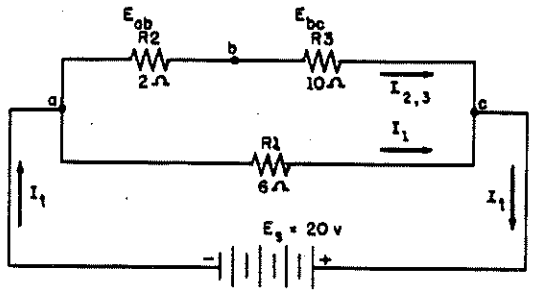
and

$$I_3 = \frac{E_{bc}}{R_3} = \frac{10}{6} = 1.666 \text{ amperes.}$$



R1 IN SERIES WITH PARALLEL COMBINATION OF R2 AND R3

(A)



R1 IN PARALLEL WITH THE SERIES COMBINATION OF R2 & R3

(B)

Figure 5-1.—Compound circuits—series-parallel connections.

According to Kirchhoff's Current Law, the sum of the currents flowing in the individual parallel branches is equal to the total current. Thus,

$$I_2 + I_3 = I_t,$$

or

$$3.333 + 1.666 = 5 \text{ amperes (approx.)}.$$

The total current flows through $R1$; and at point b it divides between the two branches in inverse proportion to the resistance of each branch. Twice as much current goes through $R2$ as through $R3$ because $R2$ has one-half the resistance of $R3$. Thus, 3.333, or two-thirds of 5, amperes flows through $R2$; and 1.666, or one-third of 5, amperes flows through $R3$.

In figure 5-1 (B), $R1$ is in parallel with the series combination of $R2$ and $R3$. The total resistance, R_t, is determined in two steps. First, the sum of the resistance of $R2$ and $R3$—that is, $R_{2,3}$—is determined as

$$R_{2,3} = R_2 + R_3 = 2 + 10 = 12 \text{ ohms.}$$

Second, the total resistance, R_t, is the result of combining $R_{2,3}$ in parallel with $R1$, or

$$R_t = \frac{R_{2,3} R_1}{R_{2,3} + R_1} = \frac{12 \times 6}{12 + 6} = 4 \text{ ohms.}$$

If the total resistance, R_t, and the source voltage, E_S, are known, the total current, I_t may be determined by Ohm's Law. Thus, in figure 5-1 (B),

$$I_t = \frac{E_s}{R_t} = \frac{20}{4} = 5 \text{ amperes.}$$

A portion of the total current flows through the series combination of $R2$ and $R3$ and the remainder flows through $R1$. Because current varies inversely with the resistance, two-thirds of the total current flows through $R1$ and one-third flows through the series combination of $R2$ and $R3$, since R_1 is one-half of $R_2 + R_3$.

The source voltage, E_S, is applied between points a and c, and therefore the current I_1 through $R1$ is

$$I_1 = \frac{E_s}{R_1} = \frac{20}{6} = 3.333 \text{ amperes;}$$

and the current, $I_{2,3}$, through $R_{2,3}$ is

$$I_{2,3} = \frac{E_s}{R_{2,3}} = \frac{20}{12} = 1.666 \text{ amperes.}$$

According to Kirchhoff's Current Law the sum of the individual branch currents is equal to the total current, or

$$I_t = I_1 + I_{2,3},$$

$$5 = 3.333 + 1.667.$$

Compound circuits may be made up of a number of resistors arranged in numerous series and parallel combinations. In more complicated circuits, special theorems, rules, and formulas are used. These are based on Ohm's Law and provide faster solutions for particular applications. Series formulas are applied to the series parts of the circuit, and parallel formulas are applied to the parallel parts. For example, in figure 5-2, the total resistance, R_t, may be obtained in three logical steps.

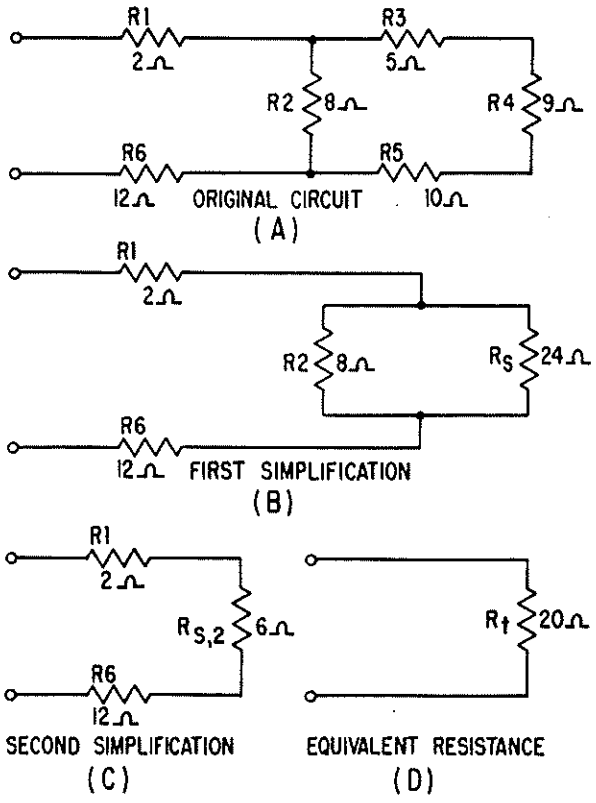


Figure 5-2.–Solving total resistance in a compound circuit.

First, $R3$, $R4$, and $R5$ in figure 5-2 (A), are in series (there is only one path for current) and may be combined in figure 5-2 (B), to give the resistance, R_S, of the three resistors. Thus,

$$R_s = R_3 + R_4 + R_5 = 5 + 9 + 10 = 24 \text{ ohms},$$

and it is now in parallel with $R2$ (because they both receive the same voltage).

The combined resistance of R_S in parallel with $R2$ is

$$R_{s,2} = \frac{R_2 R_s}{R_2 + R_s} = \frac{8 \times 24}{8 + 24} = 6 \text{ ohms},$$

as in figure 5-2 (C).

Third, the total resistance, R_t is determined by combining resistors $R1$ and $R6$ with $R_{S,2}$, as

$$R_t = R_1 + R_6 + R_{s,2} = 2 + 12 + 6 = 20 \text{ ohms}.$$

Other compound circuits may be solved in a similar manner. For example, in figure 5-3, the equivalent resistance, R_t, may be found by simplifying the circuit in successive steps beginning with the resistances, R_1 and R_2. Thus,

$$R_{1,2} = \frac{R_1 R_2}{R_1 + R_2} = \frac{3 \times 6}{3 + 6} = \frac{18}{9} = 2 \text{ ohms},$$

and it is in series with $R3$.

The resistances, $R_{1,2}$ and R_3, are added to give the resultant resistance, $R_{1,2,3}$. Thus,

$$R_{1,2,3} = R_{1,2} + R_3 = 2 + 4 = 6 \text{ ohms}.$$

$R_{1,2,3}$ is in parallel with R_4. The combined resistance, $R_{1,2,3,4}$, is determined as

$$R_{1,2,3,4} = \frac{R_{1,2,3} R_4}{R_{1,2,3} + R_4} = \frac{6 \times 12}{6 + 12} = \frac{72}{18} = 4 \text{ ohms}.$$

This equivalent resistance is in series with $R5$. Thus, the total resistance, R_t, of the circuit is

$$R_t = R_{1,2,3,4} + R_5 = 4 + 8 = 12 \text{ ohms.}$$

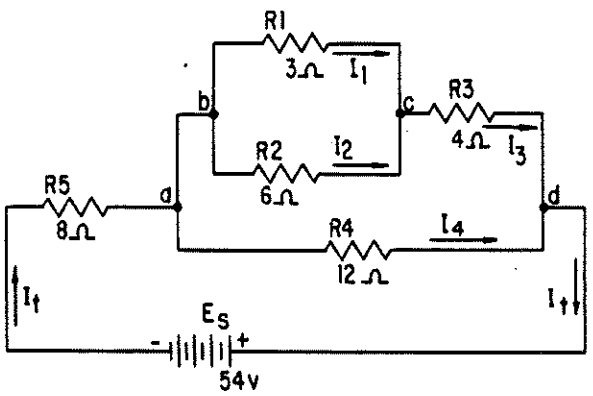


Figure 5-3.—Compound circuit for solving resistance, voltage, current, and power.

By Ohm's Law, the line current, I_t, is

$$I_t = \frac{E_s}{R_t} = \frac{54}{12} = 4.5 \text{ amperes.}$$

The line current flows through $R5$ and therefore the voltage drop, E_5, across $R5$ is

$$E_5 = I_t R_5 = 4.5 \times 8 = 36 \text{ volts.}$$

According to Kirchhoff's Voltage Law, the sum of the voltage drops around the circuit is equal to the source voltage; accordingly, the voltage between points a and d is

$$E_{ad} = E_s - E_5 = 54 - 36 = 18 \text{ volts.}$$

The current through $R4$ is

$$I_4 = \frac{E_4}{R_4} = \frac{18}{12} = 1.5 \text{ amperes.}$$

The resistance, $R_{1,2,3}$, of parallel resistors $R1$ and $R2$ in series with resistor $R3$ is 6 ohms. E_{ad} is applied across 6 ohms; therefore the current, I_3, through R3 is

$$I_3 = \frac{E_{ad}}{R_{1,2,3}} = \frac{18}{6} = 3 \text{ amperes.}$$

The voltage drop, E_3, across $R3$ is

$$E_3 = I_3 R_3 = 3 \times 4 = 12 \text{ volts.}$$

and the voltage across the parallel combination of $R1$ and $R2$—that is, E_{bc}—is

$$E_{bc} = I_{1,2} R_{1,2} = 3 \times 2 = 6 \text{ volts,}$$

where $I_{1,2}$ is the current through the parallel combinations of $R1$ and $R2$. By Kirchhoff's Current Law, $I_{1,2}$ is equal to I_3. The current, I_1 through $R1$ is

$$I_1 = \frac{E_{bc}}{R_1} = \frac{6}{3} = 2 \text{ amperes,}$$

and the current, I_2, through $R2$ is

$$I_2 = \frac{E_{bc}}{R_2} = \frac{6}{6} = 1 \text{ ampere.}$$

The preceding computations may be checked by the application of Kirchhoff's Voltage and Current Law to the entire circuit. Briefly, the sum of the voltage drops around the circuit is equal to the source voltage. Voltage E_5 across $R5$ is 36 volts and voltage E_{ad} across $R4$ is 18 volts—that is,

$$E_s = E_5 + E_{ad},$$

or

$$54 = 36 + 18 \text{ volts.}$$

Likewise, the voltage drop, E_{bc}, across the parallel combination of $R1$ and $R2$ plus the voltage drop, E_3, across $R3$ should be equal to the voltage across points a and d. E_{bc} is 6 volts and E_3 is 12 volts. Therefore,

$$E_{ad} = E_{bc} + E_3 = 6 + 12 = 18 \text{ volts.}$$

Kirchhoff's Current Law says in effect that the sum of the branch currents is equal to the line current, I_t. The line current is 4.5 amperes, and therefore the sum of I_4 and I_3 should be 4.5 amperes, or

$$I_t = I_4 + I_3 = 1.5 + 3 = 4.5 \text{ amperes.}$$

The power consumed in a circuit element is determined by one of the three power formulas. For example, in figure 5-3 the power, P_1, consumed in $R1$ is

$$P_1 = I_1 E_{bc} = 2 \times 6 = 12 \text{ watts;}$$

the power P_2 consumed in $R2$ is

$$P_2 = I_2 E_{bc} = 1 \times 6 = 6 \text{ watts;}$$

the power P_3 consumed in $R3$ is

$$P_3 = I_3 E_3 = 3 \times 12 = 36 \text{ watts;}$$

the power P_4 consumed in $R4$ is

$$P_4 = I_4 E_4 = 1.5 \times 18 = 27 \text{ watts;}$$

and the power P_5 consumed in $R5$ is

$$P_5 = I_5 E_5 = 4.5 \times 36 = 162 \text{ watts.}$$

The total power, P_t, consumed is

$$P_t = P_1 + P_2 + P_3 + P_4 + P_5$$

$$= 12 + 6 + 36 + 27 + 162$$

$$= 243 \text{ watts.}$$

The total power is also equal to the total current multiplied by the source voltage, or

$$P_t = I_t E_s = 4.5 \times 54 = 243 \text{ watts.}$$

Bridge Circuits

THE SIMPLE RESISTANCE BRIDGE

A resistance bridge circuit in its simplest form is shown in figure 5-7. Two identical resistors, $R1$ and $R2$, are connected in parallel across a 20-volt power source. The network becomes a bridge circuit when a cross connection, or "bridge" is placed between the two resistors.

Voltage across both resistors is dropped at the same rate, because the resistors are identical. Therefore, points a-a', b-b', c-c', and d-d' are at equal potentials. If the bridge is connected

between points of equal potential, as in figure 5-7 (A), no current will flow through the bridge. However, if the bridge is connected between points of unequal potential, current will flow from the more negative to the less negative end, as shown in figure 5-7 (B). In (B), current flows right-to-left from b' to d. In (C), current flows left-to-right from a to c'. Thus, it can be seen that the direction of bridge current is controlled by the relative potential of the two ends of the bridge resistor. When the bridge is across equal potentials, and no current flows, it is said to be BALANCED. When it is across unequal potentials, and current tends to flow, it is said to be UNBALANCED. The bridge may be unbalanced in either or both of two ways—(1) by connecting the bridge to unequal potentials, or (2) by using resistors of unequal values, thus causing an unbalance.

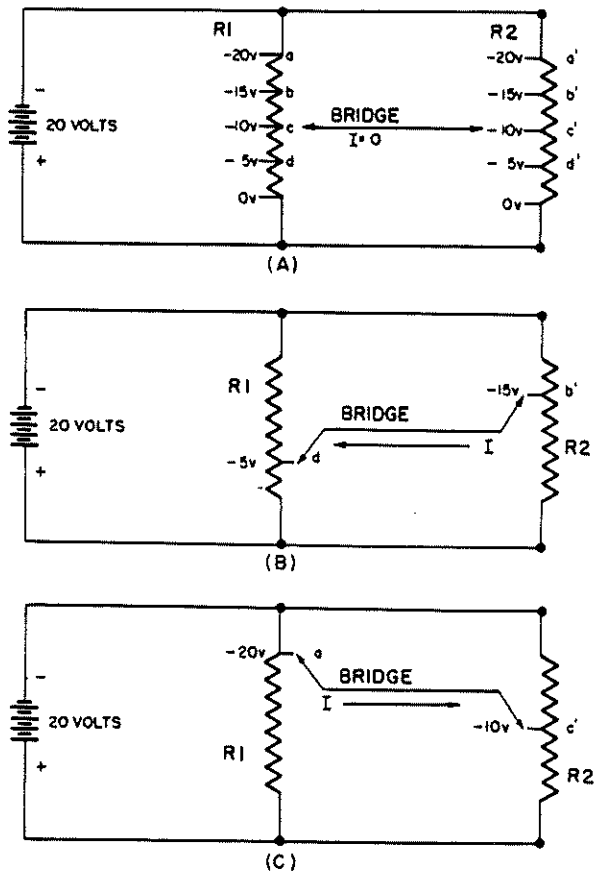


Figure 5-7.—Simple resistance bridges.

UNBALANCED RESISTANCE BRIDGE

Figure 5-8 shows an unbalanced bridge using unequal resistors. The two parallel legs are $R1$-$R4$ and $R3$-$R5$. $R2$ is the bridge. The current and voltage drop of each resistor, and the source voltage E_S, are to be determined.

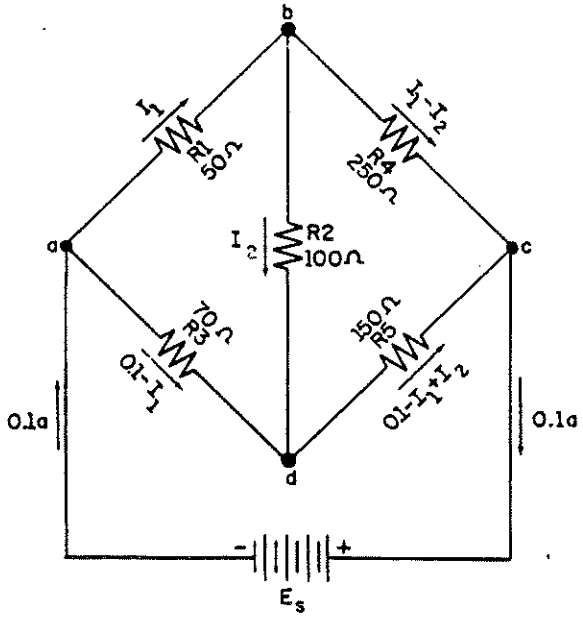


Figure 5-8.—Unbalance resistance bridge.

The current of 0.1 ampere flowing into junction a divides into two parts. The part flowing through $R1$ is indicated as I_1 and the part through $R3$ is 0.1 - I_1. Similarly, at junction b, I_1 divides, part flowing through $R2$ and the remainder through R4. The part through R2 is designated I_2 and the part through $R4$ is I_1 - I_2. The direction of current through $R2$ may be assumed arbitrarily.

If the solution indicates a positive value for I_2 the assumed direction is proved to be correct. The current through $R4$ is I_1 - I_2. At junction d the currents may be analyzed in a similar manner. Current I_2 through $R2$ joins current 0.1 - I_1, from $R3$; and the current through $R5$ is 0.1 - I_1 + I_2.

The unknown currents, I_1 and I_2, may be determined by establishing two voltage equations in which they both appear. These equations are solved for I_1 and I_2 in terms of the given values of current and resistance. The first voltage

equation is developed by tracing clockwise around the closed circuit containing resistors $R1$, $R2$, and $R3$. The trace starts at junction a, and proceeds to b, to d, and back to a. The algebraic sum of the voltages around this circuit is zero. These voltages are expressed in terms of resistance and current. Going from a to b, the voltage drop is in the direction of the arrow and is equal to $-50I_1$; the drop across $R2$, going from b to d, is $-100I_2$; and the voltage from d to a (in the opposite direction to the arrow) is $+70(0.1 - I_1)$. Thus,

$$-50I_1 - 100I_2 + 70(0.1 - I_1) = 0.$$

Multiplying both sides by -1,

$$50I + 100I_2 - 70(0.1 - I_1) = 0,$$

and transposing and simplifying,

$$120I_1 + 100I_2 = 7. \qquad (5\text{-}3)$$

The second voltage equation is established by tracing clockwise around the circuit, which includes resistors $R4$, $R5$, and $R2$. Starting at junction b, the trace proceeds to c, to d, and returns to b. The voltage across $R4$, from b to c, is $-250(I_1 - I_2)$; the voltage across $R5$, from c to d, is $+150(0.1 - I_1 + I_2)$; and the voltage across $R2$, from d to b, is $+100I_2$. Thus,

$$-250(I_1 - I_2) + 150(0.1 - I_1 + I_2) + 100I_2 = 0$$

from which,

$$400I_1 - 500I_2 = 15. \qquad (5\text{-}4)$$

Equations (5-3) and (5-4) may be solved simultaneously by multiplying equation (5-3) by the factor 5 and then adding the equations to eliminate I_2 as follows:

$$400I_1 - 500I_2 = 15$$

$$600I_1 + 500I_2 = 35$$

$$1{,}000I_1 = 50$$

$$I_1 = 0.05 \text{ ampere.}$$

Substituting the value of 0.05 for I_1 in equation (5-3) and solving for I_2,

$$120(0.05) + 100I_2 = 7$$

$$100I_2 = 1$$

$$I_2 = 0.01 \text{ ampere.}$$

Thus the current in $R1$ is $I_1 = 0.05$ ampere. The current in $R2$ is $I_2 = 0.01$ ampere. The current in $R3$ is $0.1 - I_1 = 0.1 - 0.05$, or 0.05 ampere. The current in $R4$ is $I_1 - I_2 = 0.05 - 0.01$, or 0.04 ampere. The current in $R5$ is $0.1 - I_1 + I_2 = 0.1 - 0.05 + 0.01 = 0.06$ ampere. The voltages E_1, E_2, E_3, E_4, and E_5 are as follows:

E_1 across $R1$ is $I_1R_1 = 0.05 \times 50 = 2.5$ volts.

E_2 across $R2$ is $I_2R_2 = 0.01 \times 100 = 1.0$ volts.

E_3 across $R3$ is $(0.1 - I_1)R_3 = 0.05 \times 70 = 3.5$ volts.

E_4 across $R4$ is $(I_1 - I_2)R_4 = 0.04 \times 250 = 10$ volts.

E_5 across $R5$ is $(0.1 - I_1 + I_2)R_5 = 0.06 \times 150 = 9.0$ volts.

The source voltage E_S is equal to the sum of voltages across $R3$ and $R5$ or $R1$ and $R4$. Thus,

$$E_s = E_1 + E_4$$

$$= 2.5 + 10 = 12.5 \text{ volts,}$$

and

$$E_s = E_3 + E_5$$

$$= 3.5 + 9 = 12.5 \text{ volts.}$$

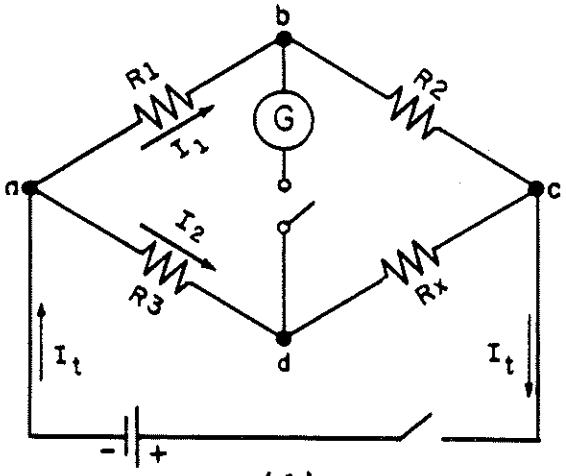
The voltage across $R2$ is the difference in the voltages across $R3$ and $R1$. It is also the difference in the voltages across $R4$ and $R5$.

WHEATSTONE BRIDGE

A type of circuit that is widely used for precision measurements of resistance is the Wheatstone bridge. The circuit diagram of a Wheatstone bridge is shown in figure 5-9 (A). $R1$, $R2$, and $R3$ are precision variable resistors, and R_X

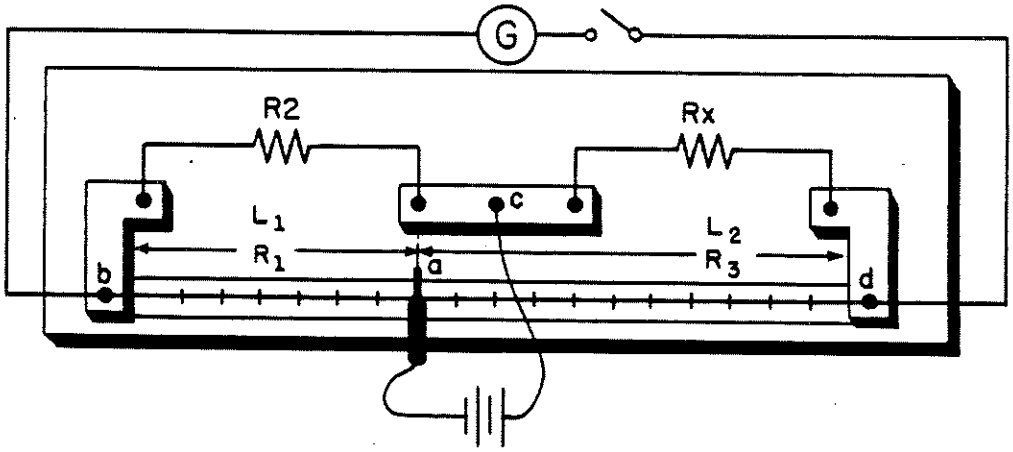
is the resistor whose unknown value of resistance is to be determined. After the bridge has been properly balanced, the unknown resistance may be determined by means of a simple formula. The galvanometer, G, is inserted across terminals b and d to indicate the condition of balance. When the bridge is properly balanced there is no difference in potential across terminals bd, and the galvanometer deflection, when the switch is closed, will be zero.

The operation of the bridge is explained in a few logical steps. When the switch to the battery is closed, electrons flow from the negative terminal of the battery to point a. Here the current divides, as it would in any parallel circuit, a part of it passing through $R1$ and $R2$ and the remainder passing through $R3$ and R_X. The two currents, labeled I_1 and I_2, unite at point c and return to the positive terminal of the battery. The value of I_1 depends on the sum of resistances R_1 and R_2, and the value of I_2 depends on the sum of resistances R_3 and R_X. In each case, according to Ohm's law, the current is inversely proportional to the resistance.



(A)

SCHEMATIC WHEATSTONE-BRIDGE CIRCUIT



(B)

SLIDE-WIRE BRIDGE

Figure 5-9.—Wheatstone bridge circuit.

$R1$, $R2$, and $R3$ are adjusted so that when the galvanometer switch is closed there will be no deflection of the needle. When the galvanometer shows no deflection there is no difference of potential between points b and d. This means that the voltage drop (E_1) across $R1$, between points a and b, is the same as the voltage drop (E_3) across $R3$, between points a and d. By similar reasoning, the voltage drops across $R2$ and R_x—that is, $E2$ and E_x—are also equal. Expressed algebraically,

$$E_1 = E_3,$$

or

$$I_1R_1 = I_2R_3,$$

and

$$E_2 = E_x,$$

or

$$I_1R_2 = I_2R_x.$$

Dividing the voltage drops across $R1$ and $R3$ by the respective voltage drops across R2 and R_x,

$$\frac{I_1R_1}{I_1R_2} = \frac{I_2R_3}{I_2R_x}.$$

Simplifying,

$$\frac{R_1}{R_2} = \frac{R_3}{R_x}.$$

Therefore,

$$R_x = \frac{R_2R_3}{R_1}.$$

The resistance values of $R1$, $R2$, and $R3$ are readily determined from the markings on the standard resistors, or from the calibrated dials if a dial-type bridge is used.

The Wheatstone bridge may be of the slide-wire type, as shown in figure 5-9 (B). In the slide-wire circuit, the slide-wire (b to d), corresponds to R_1 and R_3 of figure 5-9 (A). The wire may be an alloy of uniform cross section; for example German silver or nichrome, having a resistance of about 100 ohms. Point a is established where the slider contacts the wire. The bridge is balanced by moving the slider along the wire.

The equation for solving for R_x in the slide-wire bridge of figure 5-9 (B), is similar to the one used for solving for R_x in figure 5-9 (A). However, in the slide-wire bridge the length L_1 corresponds to the resistance R_1, and the length $L2$ corresponds to the resistance R_3. Therefore, L_1 and L_2 may be substituted for R_1 and R_3 in the equation. The resistance of L_1 and L_2 varies uniformly with slider movement because in a wire of uniform cross section the resistance varies directly with the length; therfore the ratio of the resistances equals to the corresponding ratio of the lengths. Substituting L_1 and L_2 for R_1 and R_3

$$R_x = \frac{L_2R_2}{L_1}.$$

A meter stick is mounted underneath the slide-wire and L1 and L2 are easily read in centimeters. For example, if a balance is obtained when R2 - 150 ohms, L1 25 cm. and L2 = 75 cm., the unknown resistance is

$$R_x = \frac{75}{25} \times 150 = 450 \text{ ohms.}$$

Parallel Sources Supplying A Common Load

The circuit shown in figure 5-10 illustrates two sources of e.m.f., E_{S1} and E_{S2}, having internal resistances of 2 and 2.5 ohms respectively, connected in parallel, and supplying a 5-ohm load. Neglecting the resistance of the lead wires, it is desired to determine the current delivered by each source to the load, the load current, and the load voltage.

The problem may be solved by establishing two voltage equations in which the voltages are expressed in terms of the unknown currents I_1 and I_2, the known resistances, and the known voltages. The equations are then solved simultaneously as in previous examples, to eliminate one of the unknown currents. The other unknown current is solved by substitution.

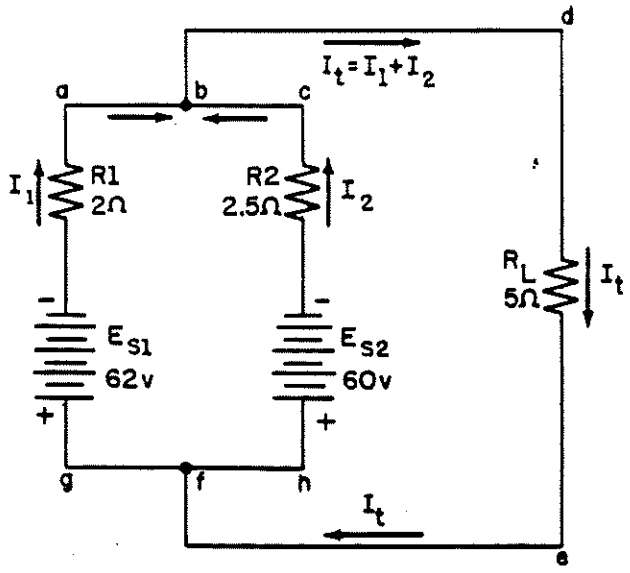


Figure 5-10.—Parallel sources supplying a common load.

The first voltage equation is established by starting at point *g* and tracing clockwise around circuit *gabdefg*. The total load current is equal to the sum of the source currents, $I_1 + I_2$. The first voltage equation is,

$$62 - 2I_1 - 5(I_1 + I_2) = 0,$$

from which,

$$7I_1 + 5I_2 = 62. \qquad (5\text{-}5)$$

The second voltage equation is established by starting at point *h* and tracing around circuit *hcbdefh*. Thus,

$$60 - 2.5I_2 - 5(I_1 + I_2) = 0,$$

from which,

$$5I_1 + 7.5I_2 = 60. \qquad (5\text{-}6)$$

I_2 is eliminated by multiplying equation (5-5) by 1.5 and subtracting equation (5-6) from the result, as follows:

$$10.5I_1 + 7.5I_2 = 93$$

$$\underline{5.0I_1 + 7.5I_2 = 60}$$

$$5.5I_1 = 33$$

$$I_1 = 6 \text{ amperes.}$$

Substituting this value in equation (5-5),

$$7 \times 6 + 5I_2 = 62,$$

from which

$$I_2 = 4 \text{ amperes.}$$

The load current is $I_1 + I_2 = 6 + 4 = 10$ amperes. Thus source E_{S1} supplies 6 amperes and source E_{S2} supplies 4 amperes.

The load voltage is equal to the voltage developed across terminals *f* and *b* and is equal to the difference in a given source voltage and the internal voltage absorbed across the corresponding source resistance.

The statement applies equally to either source since both are in parallel with the load. In terms of source E_{S1}

$$E_{fb} = E_{s1} - I_1R_1$$
$$= 62 - 6 \times 2$$
$$= 50 \text{ volts,}$$

and in terms of source E_{S2}

$$E_{fb} = E_{s2} - I_2R_2$$
$$= 60 - 4 \times 2.5$$
$$= 50 \text{ volts.}$$

A further check on the load voltage is to express this value in terms of the load current and the load resistance as follows:

$$E_{fb} = (I_1 + I_2) R_L$$
$$= (6 + 4) (5)$$
$$= 50 \text{ volts.}$$

Distribution Circuits

TWO-WIRE DISTRIBUTION CIRCUITS

Up to this point the voltage drop and the power lost in the line wires connecting the load and the source have been neglected. When the load is located at some distance from the source, the line resistance becomes an appreciable part of the total circuit resistance and the voltage and power lost in the line become significant even with moderate loads.

In figure 5-11, load *M* draws 7 amperes through terminals *b* and *e*, and the parallel group of lamps draws 5 amperes through terminals *c* and *d*. The current in line wires *bc* and *de* is 5 amperes. The line current in wires *ab* and *ef* is 5 + 7 = 12 amperes.

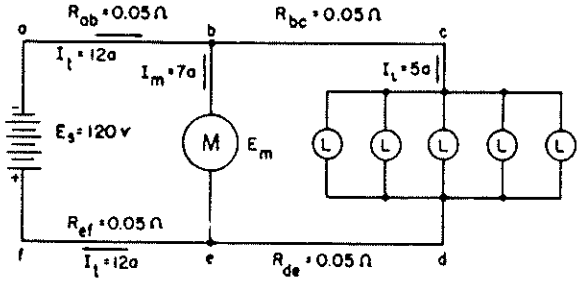


Figure 5-11.—Simple two-wire distribution circuit.

The voltage source supplies a constant potential of 120 volts between points *a* and *f*. The resistance of line wires *ab* and *ef* is 2 x 0.05 = 0.1 ohm. The voltage drop across line wires *ab* and *ef* is 12 x 0.1 = 1.2 volts. The voltage drop across line wires *bc* and *de* is 5 x 0.1 = 0.5 volt. The voltage across *M* is 120 - 1.2 = 118.8 volts and the voltage across the five lamps is 118.8 - 0.5 = 118.3 volts.

The power dissipated in line wires *ab* and *ef* is equal to $(12)^2$ x 0.1 = 144.4 watts. The power absorbed by line wires *bc* and *de* is $(5)^2$ x 0.1=2.5 watts. The total power absorbed by the line wires is 14.4 + 2.5 = 16.9 watts.

The power delivered to load *M* is 118.8 x 7 = 831.6 watts, and to the 5 lamps is 118.3 x 5 = 591.5 watts. The total power supplied to the entire circuit is equal to 16.9 + 831.6 + 591.5 = 1,440 watts and is equal to the product of the total applied voltage and the total current. Thus,

$$P_t = E_t I_t = 120 \times 12 = 1{,}440 \text{ watts.}$$

THREE-WIRE DISTRIBUTION CIRCUITS

Three-wire distribution circuits transmit power at 240 volts and utilize it at 120 volts. The direct-current 3-wire system includes a positive feeder, a negative feeder, and a neutral wire, as shown in figure 5-12 (A). The loads are connected between the negative feeder and the neutral, and between the positive feeder and the neutral. When the loads are unbalanced (unequal) the neutral wire carries a current equal to the difference in the currents in the negative and positive feeders.

In the example of figure 5-12 (A), load *L*1 draws 10 amperes, load *L*2 draws 4 amperes, and the neutral wire carries a current of 10 - 4 = 6 amperes. The direction of flow of the current in the neutral wire is always the same as that of the smaller of the currents in the positive and negative feeders. Thus the flow is to the left in the lower (positive) wire and also in the neutral. The current in the upper (negative) wire is 10 amperes and in the lower wire is 4 amperes. The algebraic sum of the currents entering and leaving junction *c* is equal to zero. Thus,

$$+ 10 - 6 - 4 = 0.$$

To find load voltage, E_1, a voltage equation is established in which E_1 is expressed in terms of the source voltage, E_{S1}, and the *IR* drops in the negative feeder and neutral wire. The algebraic sum of the voltages around the circuit *fabcf*, is equal to zero. Starting at *f* and proceeding clockwise,

$$+ 120 - 10 \times 0.5 - E_1 - 6 \times 0.5 = 0$$

$$E_1 = 112 \text{ volts.}$$

Thus the voltage across load *L*1 is 112 volts. This voltage is less than the source voltage by an amount equal to the sum of the voltage drops in

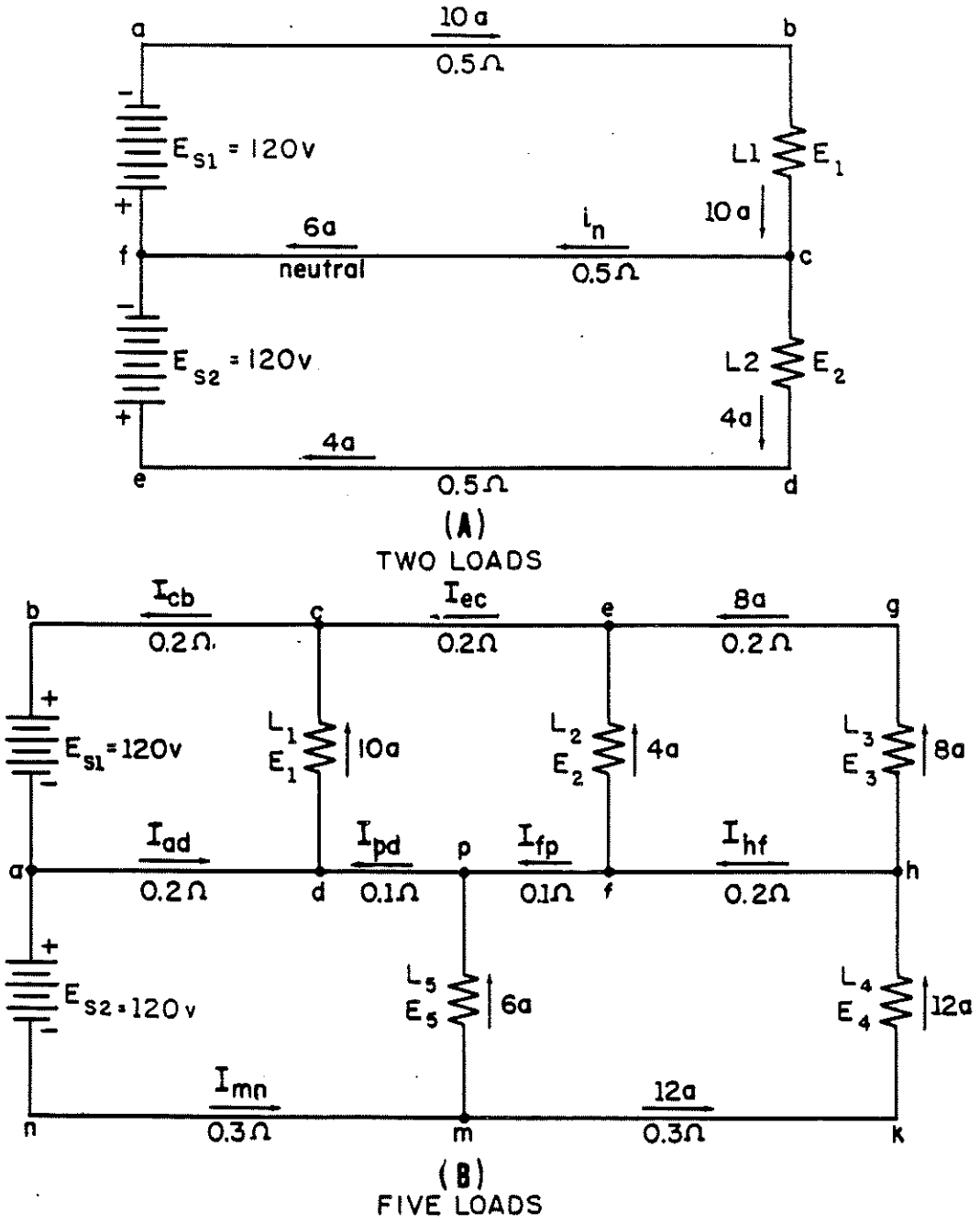


Figure 5-12.—Three-wire distribution circuits.

the negative (5 volts) and the neutral (3 volts) wires.

To find load voltage E_2 a voltage equation is established in which E_2 is expressed in terms of the source voltage, E_{S2}, and the IR drops in the positive feeder and the neutral wire. The algebraic sum of the voltages around the circuit *efcde* is zero. Starting at *e* and proceeding clockwise,

$$+120 + (6 \times 0.5) - E_2 - (4 \times 0.5) = 0$$

$$E_2 = 121 \text{ volts.}$$

In tracing the circuit from f to c note that the direction is against the arrow representing current flow, and therefore that the IR drop of (6 x 0.5) volts is preceded by a plus sign. The load voltage, E_2, is 121 volts, which is 1 volt higher than the source voltage, E_{S2}. The total source voltage ($E_{S1} + E_{S2}$) is 240 volts and the total load voltage ($E_1 + E_2$) is 112 + 121 = 233 volts. This value is also equal to the difference between the total source voltage and the sum of the voltage drops in the positive and negative feeders, or 240 - (2 + 5) = 233 volts.

When the loads are balanced on the positive and negative sides of the 3-wire system, the neutral current is zero and the currents in the outside wires (positive and negative) are equal. When the loads are unbalanced the neutral wire carries the unbalanced current. The voltage on the heavily loaded side falls while the voltage on the lightly loaded side rises. The lower the resitance of the neutral wire, the less unbalance in voltage there will be for a given unbalanced load.

A more complicated 3-wire circuit is shown in figure 5-12 (B). The source voltage is 120 volts between each outside wire and the neutral, or center, wire. Load currents in the upper side of the system are indicated as 10, 4, and 8 amperes respectively for loads 1, 2, and 3. In the lower side of the system, the load currents are 12 and 6 amperes respectively for loads 4 and 5. In order to determine the various load voltages it is necessary to find the currents in each outside wire and in the neutral wire. The resistances of these wires are indicated, and therefore the voltage drops and the load voltages may be calculated after the currents are determined.

To find the currents in the various sections of the wires, it is best to start at the load farthest removed from the source. The polarities of the sources are such that electrons flow out of the negative terminal at n and return to the positive terminal at b.

Currents flowing toward a junction are assumed to be positive, and those flowing away from a junction are assumed to be negative. Applying Kirchhoff's Current Law at junction h, the neutral current, I_n (flowing from h to f) is determined as

$$12 - 8 - I_{hf} = 0$$

$$I_{hf} = 4 \text{ amperes.}$$

Applying the same rule successively to junctions f, e, p, m, d, and c, it follows that:

at junction f,

$$4 - 4 - I_{fp} = 0$$

$$I_{fp} = 0 \text{ ampere,}$$

at junction e,

$$4 + 8 - I_{ec} = 0$$

$$I_{ec} = 12 \text{ amperes,}$$

at junction p,

$$6 + 0 - I_{pd} = 0$$

$$I_{pd} = 6 \text{ amperes,}$$

at junction m,

$$+ I_{mn} - 6 - 12 = 0$$

$$I_{mn} = 18 \text{ amperes,}$$

at junction d,

$$I_{ad} + 6 - 10 = 0$$

$$I_{ad} = 4 \text{ amperes,}$$

at junction c,

$$I_{cb} + 10 + 12 = 0$$

$$I_{cb} = 22 \text{ amperes.}$$

Thus, E_{S1} supplies 22 amperes and E_{S2} supplies 18 amperes. The electron flow in all parts of the lower wire is outward from the source, and the electron flow in all parts of the upper wire is back toward the source. The current in the neutral wire is always equal to the difference in the currents in the two outside wires, and the electron flow is in the direction of the smaller of these two currents. Thus in figure 5-12 (B), the neutral current in section ad is 4 amperes, which is the difference between 18 amperes and 22 amperes; and it is in the direction of the smaller current in section nm. The neutral current in section pd is 6 amperes, which is the difference between 18 amperes and 12 amperes; and it is in the same direction as the 12 amperes in section ec. The neutral current in section fp is zero because the current in

each outside wire in that section is 12 amperes. The neutral current in section *hf* is 4 amperes, which is the difference between 12 amperes and 8 amperes, and it is in the direction of the smaller outside current in section *ge*.

In order to find the voltages across the loads in figure 5-12 (B), Kirchhoff's Voltage Law is applied to the various individual circuits. Thus to find the voltage, E_1, across load L_1, the algebraic sum of the voltages around the circuit *abcda* is equated to zero, and E_1 is then readily determined. Starting at *a*,

$$-120 + (22 \times 0.2) + E_1 + (4 \times 0.2) = 0$$

$$E_1 = 114.8 \text{ volts.}$$

To find load voltage E_2, the algebraic sum of the voltages around circuit *dcefpd* is set equal to zero. Starting at *d*,

$$-114.8 + (12 \times 0.2) + E_2 + (0 \times 0.1) - (6 \times 0.1) = 0$$

$$E_2 = 113 \text{ volts.}$$

To find load voltage E_3, the algebraic sum of the voltages around loop *feghf* is set equal to zero. Starting at *f*,

$$-113 + (8 \times 0.2) + E_3 - (4 \times 0.2) = 0$$

$$E_3 = 112.2 \text{ volts.}$$

To find load voltage E_4, the algebraic sum of the voltages around loop *nadpfhkmn* is set equal to zero. Loop *mpfhkm* cannot be used because it would contain two unknown voltages, E_5 and E_4. Starting at *n*,

$$-120 - (4 \times 0.2) + (6 \times 0.1) + (0 \times 0.1) + (4 \times 0.2) + E_4 + (12 \times 0.3) + (18 \times 0.3) = 0$$

$$E_4 = 110.4 \text{ volts.}$$

To find load voltage E_5, the algebraic sum of the voltages around loop *nadpmn* is set equal to zero. Starting at *n*,

$$-120 - (4 \times 0.2) + (6 \times 0.1) + E_5 + (18 \times 0.3) = 0$$

$$E_5 = 114.8 \text{ volts.}$$

In each case, the equations used contain one unknown; and thus a simple solution is quickly obtained. It is necessary that the path traced include a completely closed loop and that all but one of the voltages within that loop be known. Simple transposition of the resulting equation gives the desired voltage.

QUIZ

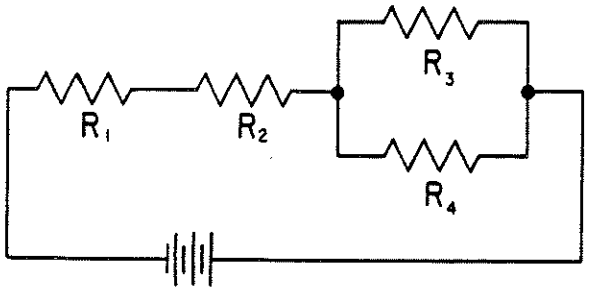
1. The minimum number of resistors in a compound circuit is/are
   a. four
   b. three
   c. two
   d. one
2. Total resistance of the circuit shown is determined by the formula

   a. $R_1R_2 + \dfrac{R_3R_4}{R_4 + R_3}$

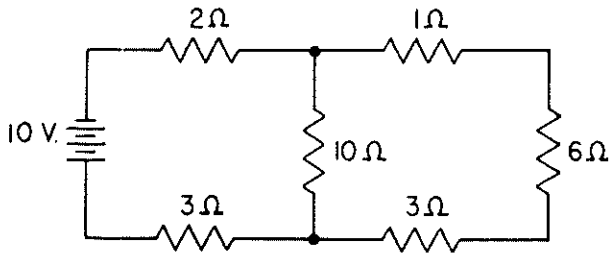
   b. $R_1 + R_2 + \dfrac{R_3 + R_4}{R_3R_4}$

   c. $R_1 + R_2 + \dfrac{R_3R_4}{R_3 + R_4}$

   d. $R_1 + R_2 \left(\dfrac{R_3R_4}{R_3 + R_4}\right)$



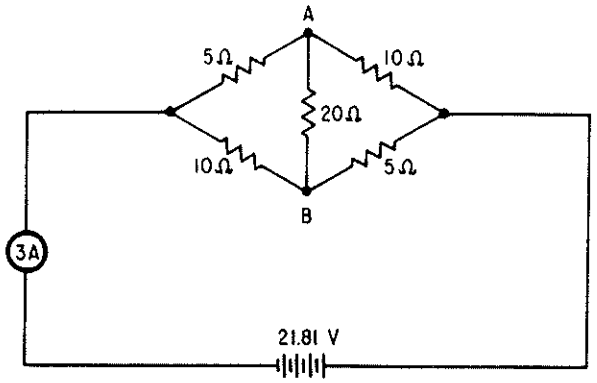
3. In the circuit below -- what is the value of I_t?
   a. I_t = 1.14 amp
   b. I_t = 0.4 amp
   c. I_t = 0.667 amp
   d. I_t = 1 amp



4. In the circuit in question 3, how much power is consumed by the 6-ohm resistor?
   a. 15 watts
   b. 1.5 watts
   c. 60 watts
   d. 6 watts

5. What two conditions may be observed in a bridge circuit?
   a. T and L network characteristics
   b. No-load and full-load bridge current
   c. Unequal potential and unequal current
   d. Balance and unbalance

6. In the circuit below—how much current flows in the 20θ resistor and what is its direction?
   a. 26 a., B to A
   b. 1 a., A to B
   c. 0.26 a., A to B
   d. 1 a., B to A



7. In a three-wire distribution system, an unbalanced situation is indicated by the
   a. potential of the positive wire being equal to the negative wire
   b. positive wire carrying more amperage than the negative wire
   c. current in the neutral wire
   d. neutral wire carrying the total current

8. In figure 5-9 (A), the galvanometer will show zero deflection when

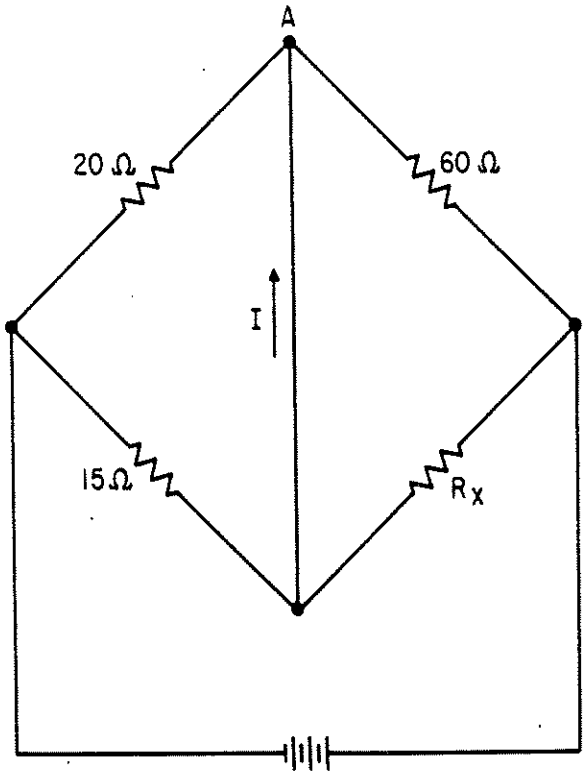
   a. $\frac{R_1}{R_2} = \frac{R_3}{R_x}$

   b. $R_x = \frac{R_1 R_3}{R_2}$

   c. $\frac{I_1 R_1}{I_2 R_x} = \frac{I_2 R_3}{I_1 R_2}$

   d. $R_x = \frac{R_1 R_2}{R_3}$

9. In the Wheatstone bridge type circuit below, the bridge current is toward point A. The resistance of R_X is
   a. 30Ω
   b. greater than 45Ω
   c. 20Ω
   d. less than 15Ω



10. In the slide-wire bridge, shown in figure 5-9 (B), L_1 is equal to

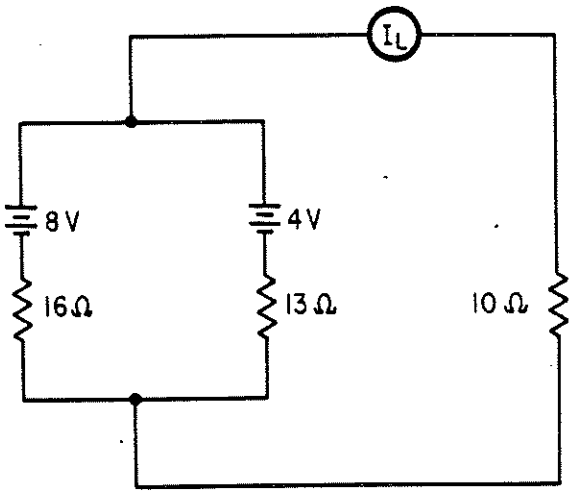
    a. $L_1 = \frac{R_2 L_2}{R_1}$

    b. $L_1 = \frac{R_1 + L_2}{R_2}$

    c. $\frac{R_2}{R_1 L_2} = L_1$

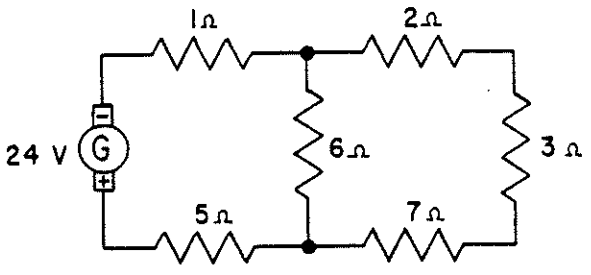
    d. $\frac{R_2 L_2}{R_X} = L_1$

11. In the circuit below I line is
    a. 4.44 a.
    b. 0.444 a.
    c. 0.337 a.
    d. 5.22 a.



12. When checking a 3-wire distribution circuit going against the direction of current flow the IR drop is always
    a. negative
    b. positive
    c. not used
    d. always in direction of current flow

13. In the circuit below, the voltage drop across the 3-ohm resistor is
    a. 2.4 volts
    b. 24 volts
    c. 9.6 volts
    d. 0.96 volts



CHAPTER 6

ELECTRICAL CONDUCTORS AND WIRING TECHNIQUES

Since all electrical circuits utilize conductors of one type of another, it is essential that you know the basic physical features and electrical characteristics of the most common types of conductors.

As stated previously, any substance that permits the free motion of a large number of electrons is classed as a conductor. A conductor may be made from many different types of metals, but only the most commonly used types of materials will be discussed in this chapter.

To compare the resistance and size of one conductor with that of another, a standard or unit size of conductor must be established. A convenient unit of linear measurement, as far as the diameter of a piece of wire is concerned, is the mil (0.001 of an inch); and a convenient unit of wire length is the foot. The standard unit of size in most cases is the MIL-FOOT. That is, a wire will have unit size if it has diameter of 1 mil and a length of 1 foot. The resistance in ohms of a unit conductor of a given substance is called the specific resistance, or specific resistivity, of the substance.

Gage numbers are a further convenience in comparing the diameter of wires. The gage commonly used is the American wire gage (AWG), formerly the Brown and Sharpe (B and S) gage.

SQUARE MIL

The square mil is a convenient unit of cross-sectional area for square or rectangular conductors. A square mil is the area of a square, the sides of which are 1 mil, as shown in figure 6-1 (A). To obtain the cross-sectional area in square mils of a square conductor, square one side measured in mils. To obtain the cross-sectional area in square mils of a rectangular conductor, multiply the length of one side by that of the other, each length being expressed in mils.

For example, find the cross-sectional area of a large rectangular conductor 3/8 inch thick and 4 inches wide. The thickness may be expressed in mils as 0.375 x 1,000 = 375 mils, and the width as 4 x 1,000, or 4,000 mils. The cross-sectional area is 375 x 4,000, or 1,500,000 square mils.

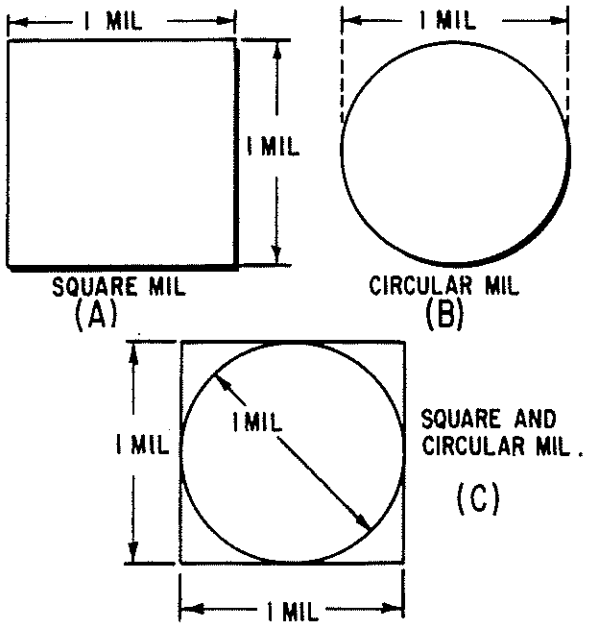


Figure 6-1.—(A) Square mil; (B) circular mil; (C) comparison of circular to square mil.

CIRCULAR MIL

The circular mil is the standard unit of wire cross-sectional area used in American and English wire tables. Because the diameters of round conductors, or wires, used to conduct electricity may be only a small fraction of an inch, it is convenient to express these diameters

in mils, to avoid the use of decimals. For example, the diameter of a wire is expressed as 25 mils instead of 0.025 inch. A circular mil is the area of a circle having a diameter of 1 mil, as shown in figure 6-1 (B). The area in circular mils of a round conductor is obtained by squaring the diameter measured in mils. Thus, a wire having a diameter of 25 mils has an area of 25^2 or 625 circular mils. By way of comparison, the basic formula for the area of a circle is $A = \pi R^2$ and in this example the area in square inches is

$$A = \pi R^2 = 3.14(0.0125)^2 = 0.00049 \text{ sq. in.}$$

If D is the diameter of a wire in mils, the area in square mils is

$$A = \pi \left(\frac{D}{2}\right)^2 = \frac{3.1416}{4} D^2 = 0.7854D^2 \text{ sq. mils.}$$

Therefore, a wire 1 mil in diameter has an area of

$$A = 0.7854 \times 1^2 = 0.7854 \text{ sq. mils,}$$

which is equivalent to 1 circular mil. The cross-sectional area of a wire in circular mils is therefore determined as

$$A = \frac{0.7854D^2}{0.7854} \quad D^2 \text{ circular mils,}$$

where D is the diameter in mils. Thus, the constant $\frac{\pi}{4}$ is eliminated from the calculation.

In comparing square and round conductors it should be noted that the circular mil is a smaller unit of area than the square mil, and therefore there are more circular mils than square mils in any given area. The comparison is shown in figure 6-1 (C). The area of a circular mil is equal to 0.7854 of a square mil. Therefore, to determine the circular-mil area when the square-mil area is given, divide the area in square mils by 0.7854. Conversely, to determine the square-mil area when the circular-mil area is given, multiply the area in circular mils by 0.7854.

For example, a No. 12 wire has a diameter of 80.81 mils. What is (1) its area in circular mils and (2) its area in square mils?

Solution:

(1) $A = D^2 = 80.81^2 = 6,530$ circular mils.

(2) $A = 0.7854 \times 6,530 = 5,128.7$ square mils.

A rectangular conductor is 1.5 inches wide and 0.25 inch thick. (1) What is its area in square mils? (2) What size of round conductor in circular mils is necessary to carry the same current as the rectangular bar?

Solution:

(1) $1.5'' = 1.5 \times 1,000 = 1,500$ mils

$0.25'' = 0.25 \times 1,000 = 250$ mils

$A = 1,500 \times 250 = 375,000$ square mils.

(2) To carry the same current, the cross-sectional area of the rectangular bar and the cross-sectional area of the round conductor must be equal. There are more circular mils than square mils in this area, and therefore

$$A = \frac{375,000}{0.7854} = 477,000 \text{ circular mils.}$$

A wire in its usual form is a slender rod or filament of drawn metal. In large sizes, wire becomes difficult to handle, and its flexibility is increased by stranding. The strands are usually single wires twisted together in sufficient numbers to make up the necessary cross-sectional area of the cable. The total area in circular mils is determined by multiplying the area of one strand in circular mils by the number of strands in the cable.

CIRCULAR-MIL-FOOT

A circular-mil-foot, as shown in figure 6-2, is actually a unit of volume. It is a unit conductor 1 foot in length and having a cross-sectional area of 1 circular mil. Because it is considered a unit conductor, the circular-mil-foot is useful in making comparisons between wires that are made of different metals. For example, a basis of comparison of the RESISTIVITY (to be treated later) of various substances may be made by determining the resistance of a circular-mil-foot of each of the substances.

In working with certain substances it is sometimes more convenient to employ a different unit volume. Accordingly, unit volume may also be taken as the centimeter cube; and specific resistance becomes the resistance offered by a cube-shaped conductor 1 cm. long and 1 sq. cm. in cross-sectional area. The inch

cube may also be used. The unit of volume employed is given in tables of specific resistances.

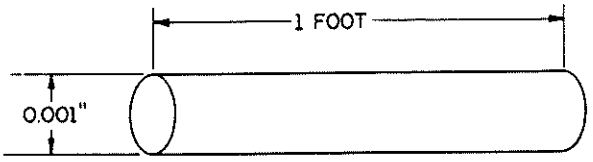


Figure 6-2.—Circular-mil-foot.

WIRE MEASURE

Relation Between Wire Sizes

Wires are manufactured in sizes numbered according to a table known as the American wire gage (AWG). As may be seen in table 6-3, the wire diameters become smaller as the gage numbers become larger. The largest wire size shown in the table is 0000 (read "4 naught"), and the smallest is number 40. Larger and smaller sizes are manufactured but are not commonly used by the Navy. The ratio of the diameter of one gage number to the diameter of the next higher gage number is a constant, 1.123. The cross-sectional area varies as the square of the diameter. Therefore, the ratio of the cross section of one gage number to that of the next higher gage number is the square of 1.123, or 1.261. Because the cube of 1.261 is very nearly 2, the cross-sectional area is approximately halved, or doubled, every three gage numbers. Also because 1.261 raised to the 10th power is very nearly equal to 10, the cross-sectional area is increased or decreased 10 times every 10 gage numbers.

A No. 10 wire has a diameter of approximately 102 mils, a cross-sectional area of approximately 10,400 circular mils, and a resistance of approximately 1 ohm per 1,000 feet. From these facts it is possible to estimate quickly the cross-sectional area and the resistance of any size copper wire without referring directly to a wire table.

For example, to estimate the cross-sectional area and the resistance of 1,000 feet of No. 17 wire, the following reasoning might be employed. A No. 17 wire is 3 sizes removed from a No. 20 wire and therefore has twice the cross-sectional area of a No. 20 wire. A No. 20 wire is 10 sizes removed from a No. 10 wire and therefore has one-tenth the cross section of a No. 10 wire. Therefore, the cross-sectional area of a No. 17 wire is 2 x 0.1 x 10,000 = 2,000 circular mils. Since resistance varies inversely with the cross-sectional area, the resistance of a No. 17 wire is 10 x 1 x 0.5 = 5 ohms per 1,000 feet.

A wire gage is shown in figure 6-3. It will measure wires ranging in size from number 0 to number 36. The wire whose size is to be measured is inserted in the smallest slot that will just accommodate the bare wire. The gage number corresponding to that slot indicates the wire size. The slot has parallel sides and should not be confused with the semicircular opening at the end of the slot. The opening simply permits the free movement of the wire all the way through the slot.

Stranded Wires and Cables

A WIRE is a slender rod or filament of drawn metal. The definition restricts the term to what would ordinarily be understood as "solid wire." The word "slender" is used because the length of a wire is usually large in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire. Although the term "wire" properly refers to the metal, it is generally understood to include the insulation.

A CONDUCTOR is a wire or combination of wires not insulated from one another, suitable for carrying an electric current.

A STRANDED CONDUCTOR is a conductor composed of a group of wires or of any combination of groups of wires. The wires in a stranded conductor are usually twisted together.

A CABLE is either a stranded conductor (single-conductor cable) or a combination of conductors insulated from one another (multiple-conductor cable). The term cable is a general one, and in practice it is usually applied only to the larger sizes of conductors. A small cable is more often called a stranded wire or cord. Cables may be bare or insulated. The insulated cables may be sheathed (covered) with lead, or protective armor.

Figure 6-4 shows some of the different types of wire and cables used.

Conductors are stranded mainly to increase their flexibility. The arrangement of the wire strands in concentric-layer cables is as follows:

Table 6-3.—Standard annealed solid copper wire.

(American wire gage—B & S)

Gage number	Diameter (mils)	Cross section		Ohms per 1,000 ft.		Ohms per mile	Pounds per 1,000 ft.
		Circular mils	Square inches	25° C. (= 77° F.)	65° C. (= 149° F.)	25° C. (= 77° F.)	
0000	460.0	212,000.0	0.166	0.0500	0.0577	0.264	641.0
000	410.0	168,000.0	.132	.0630	.0727	.333	508.0
00	365.0	133,000.0	.105	.0795	.0917	.420	403.0
0	325.0	106,000.0	.0829	.100	.116	.528	319.0
1	289.0	83,700.0	.0657	.126	.146	.665	253.0
2	258.0	66,400.0	.0521	.159	.184	.839	201.0
3	229.0	52,600.0	.0413	.201	.232	1.061	159.0
4	204.0	41,700.0	.0328	.253	.292	1.335	126.0
5	182.0	33,100.0	.0260	.319	.369	1.685	100.0
6	162.0	26,300.0	.0206	.403	.465	2.13	79.5
7	144.0	20,800.0	.0164	.508	.586	2.68	63.0
8	128.0	16,500.0	.0130	.641	.739	3.38	50.0
9	114.0	13,100.0	.0103	.808	.932	4.27	39.6
10	102.0	10,400.0	.00815	1.02	1.18	5.38	31.4
11	91.0	8,230.0	.00647	1.28	1.48	6.75	24.9
12	81.0	6,530.0	.00513	1.62	1.87	8.55	19.8
13	72.0	5,180.0	.00407	2.04	2.36	10.77	15.7
14	64.0	4,110.0	.00323	2.58	2.97	13.62	12.4
15	57.0	3,260.0	.00256	3.25	3.75	17.16	9.86
16	51.0	2,580.0	.00203	4.09	4.73	21.6	7.82
17	45.0	2,050.0	.00161	5.16	5.96	27.2	6.20
18	40.0	1,620.0	.00128	6.51	7.51	34.4	4.92
19	36.0	1,290.0	.00101	8.21	9.48	43.3	3.90
20	32.0	1,020.0	.000802	10.4	11.9	54.9	3.09
21	28.5	810.0	.000636	13.1	15.1	69.1	2.45
22	25.3	642.0	.000505	16.5	19.0	87.1	1.94
23	22.6	509.0	.000400	20.8	24.0	109.8	1.54
24	20.1	404.0	.000317	26.2	30.2	138.3	1.22
25	17.9	320.0	.000252	33.0	38.1	174.1	0.970
26	15.9	254.0	.000200	41.6	48.0	220.0	0.769
27	14.2	202.0	.000158	52.5	60.6	277.0	0.610
28	12.6	160.0	.000126	66.2	76.4	350.0	0.484
29	11.3	127.0	.0000995	83.4	96.3	440.0	0.384
30	10.0	101.0	.0000789	105.0	121.0	554.0	0.304
31	8.9	79.7	.0000626	133.0	153.0	702.0	0.241
32	8.0	63.2	.0000496	167.0	193.0	882.0	0.191
33	7.1	50.1	.0000394	211.0	243.0	1,114.0	0.152
34	6.3	39.8	.0000312	266.0	307.0	1,404.0	0.120
35	5.6	31.5	.0000248	335.0	387.0	1,769.0	0.0954
36	5.0	25.0	.0000196	423.0	488.0	2,230.0	0.0757
37	4.5	19.8	.0000156	533.0	616.0	2,810.0	0.0600
38	4.0	15.7	.0000123	673.0	776.0	3,550.0	0.0476
39	3.5	12.5	.0000098	848.0	979.0	4,480.0	0.0377
40	3.1	9.9	.0000078	1,070.0	1,230.0	5,650.0	0.0299

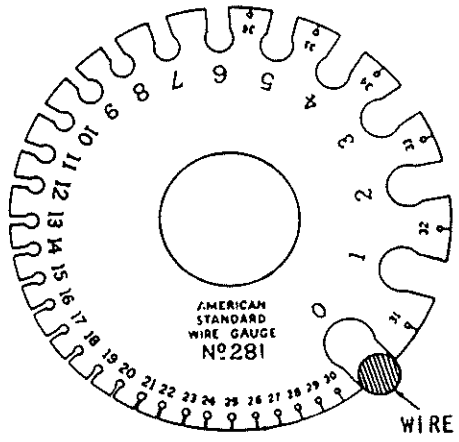


Figure 6-3.—Wire gage.

The first layer of strands around the center is made up of 6 conductors; the second layer is made up of 12 conductors; the third layer is made up of 18 conductors; and so on. Thus, standard cables are composed of 1, 7, 19, 37, and so forth strands.

The overall flexibility may be increased by further stranding of the individual strands.

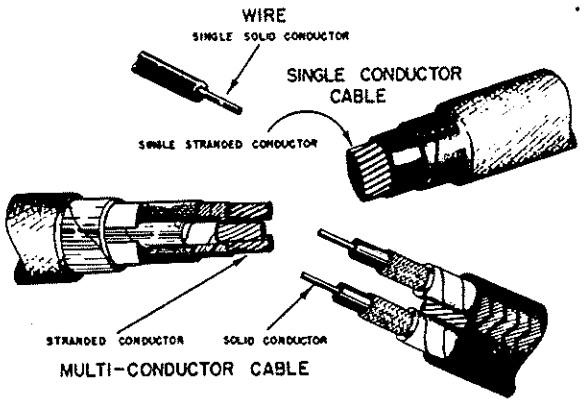
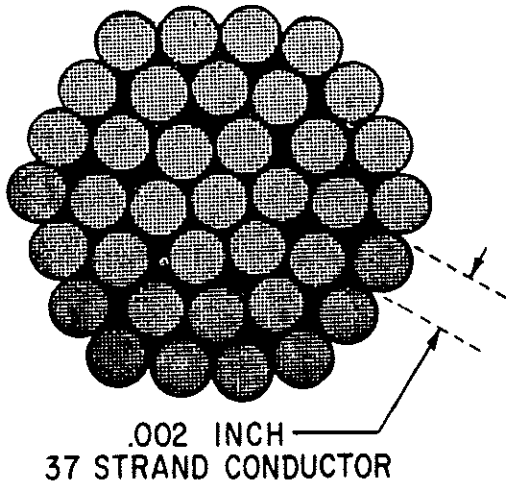


Figure 6-4.—Conductors.

Figure 6-5 shows a typical 37-strand cable. It also shows how the total circular-mil cross-sectional area of a stranded cable is determined.



DIAMETER OF EACH STRAND = .002 INCH
DIAMETER OF EACH STRAND, MILS = 2 MILS
CIRCULAR MIL AREA OF
EACH STRAND = D^2 = 4 CM
TOTAL CM AREA OF
CONDUCTOR = 4 x 37 = 148 CM

Figure 6-5.—Stranded conductor.

Factors Governing the Selection of Wire Size

Several factors must be considered in selecting the size of wire to be used for transmitting and distributing electric power.

One factor is the allowable power loss (I^2R loss) in the line. This loss represents electrical energy converted into heat. The use of large conductors will reduce the resistance and therefore the I^2R loss. However, large conductors are more expensive initially than small ones; they are heavier and require more substantial supports.

A second factor is the permissible voltage drop (IR drop) in the line. If the source maintains a constant voltage at the input to the line, any variation in the load on the line will cause a variation in line current, and a consequent variation in the IR drop in the line. A wide variation in the IR drop in the line causes poor voltage regulation at the load. The obvious remedy is to reduce either I or R. A reduction in load current lowers the amount of power being transmitted, whereas a reduction in line resistance increases the size and weight of conductors required. A compromise is generally reached whereby the voltage variation at the load is within tolerable limits and the weight of line conductors is not excessive.

A third factor is the current-carrying ability of the line. When current is drawn through the line, heat is generated. The temperature of the line will rise until the heat radiated, or otherwise dissipated, is equal to the heat generated by the passage of current through the line. If the conductor is insulated, the heat generated in the conductor is not so readily removed as it would be if the conductor were not insulated. Thus, to protect the insulation from too much heat, the current through the conductor must be maintained below a certain value. Rubber insulation will begin to deteriorate at relatively low temperatures. Varnished cloth insulation retains its insulating properties at higher temperatures; and other insulation—for example, asbestos or silicon—is effective at still higher temperatures.

Electrical conductors may be installed in locations where the ambient (surrounding) temperature is relatively high; in which case the heat generated by external sources constitutes an appreciable part of the total conductor heating. Due allowance must be made for the influence of external heating on the allowable conductor current and each case has its own specific limitations. The maximum allowable operating temperature of insulated conductors is specified in tables and varies with the type of conductor insulation being used.

Tables have been prepared by the National Board of Fire Underwriters giving the safe current ratings for various sizes and types of conductors covered with various types of insulation. For example, the allowable current-carrying capacities of copper conductors at not over 30° C. (86° F.) room temperature for single conductors in free air are given in table 6-4.

COPPER VS. ALUMINUM CONDUCTORS

Although silver is the best conductor, its cost limits its use to special circuits where a substance with high conductivity is needed.

The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances. Likewise, each has certain disadvantages.

Copper has a higher conductivity; it is more ductile (can be drawn out), has relatively high tensile strength, and can be easily soldered. It is more expensive and heavier than aluminum.

Although aluminum has only about 60 percent of the conductivity of copper, it is used extensively for high-voltage transmission lines. Its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona—that is, the discharge of electricity from the wire when it has a high potential. The discharge is greater when smaller diameter wire is used than when larger diameter wire is used. However, aluminum conductors are not easily soldered, and aluminum's relatively large size for a given conductance does not permit the economical use of an insulation covering.

A comparison of some of the characteristics of copper and aluminum is given in table 6-5.

TEMPERATURE COEFFICIENT OF RESISTANCE

The resistance of pure metals—such as silver, copper, and aluminum—increases as the temperature increases. However, the resistance of some alloys—such as constantan and manganin—changes very little as the temperature changes. Measuring instruments use these alloys because the resistance of the circuits must remain constant if accurate measurements are to be achieved.

In table 6-1 the resistance of a circular-mil-foot of wire (the specific resistance) is given at a specific temperature, 20° C. in this case. It is necessary to establish a standard temperature because, as has been stated, the resistance of pure metals increase with an increase in temperature; and a true basis of comparison cannot be made unless the resistances of all the substances being compared are measured at the same temperature. The amount of increase in the resistance of a 1-ohm sample of the conductor per degree rise in temperature above 0° C. is called the TEMPERATURE COEFFICIENT OF RESISTANCE. For copper, the value is approximately 0.00427 ohms. For pure metals, the temperature coefficient of resistance ranges between 0.003 and 0.006 ohms.

Thus, a copper wire having a resistance of 50 ohms at an initial temperature of 0° C. will have an increase in resistance of 50 x 0.00427, or 0.214 ohms for the entire length of wire for each degree of temperature rise above 0° C. At 20° C. the increase in resistance is approximately 20 x 0.214, or 4.28 ohms. The total resistance at 20° C. is 50 + 4.28, or 54.28 ohms.

Table 6-4.—Current-carrying capacities (in amperes) of single copper conductors at ambient temperature of below 30° C.

Size	Rubber or thermoplastic	Thermoplastic asbestos, var-cam, or asbestos var-cam	Impregnated asbestos	Asbestos	Slow-burning or weatherproof
0000	300	385	475	510	370
000	260	330	410	430	320
00	225	285	355	370	275
0	195	245	305	325	235
1	165	210	265	280	205
2	140	180	225	240	175
3	120	155	195	210	150
4	105	135	170	180	130
6	80	100	125	135	100
8	55	70	90	100	70
10	40	55	70	75	55
12	25	40	50	55	40
14	20	30	40	45	30

Table 6-5.—Characteristics of copper and aluminum.

Characteristics	Copper	Aluminum
Tensile strength (lb/in^2).	55,000	25,000
Tensile strength for same conductivity (lb).	55,000	40,000
Weight for same conductivity (lb).	100	48
Cross section for same conductivity (C.M.).	100	160
Specific resistance (Ω/mil ft).	10.6	17

CONDUCTOR INSULATION

To be useful and safe, electric current must be forced to flow only where it is needed. It must be "channeled" from the power source to a useful load. In general, current-carrying conductors must not be allowed to come in contact with one another, their supporting hardware, or personnel working near them. To accomplish this, conductors are coated or wrapped with various materials. These materials have such a high resistance that they are, for all practical purposes, nonconductors. They are generally referred to as insulators or insulating material.

Because of the expense of insulation and its stiffening effect, together with the great variety of physical and electrical conditions under which the conductors are operated, only the necessary minimum of insulation is applied for any particular type of cable designed to do a specific job. Therefore there is a wide variety of insulated conductors available to meet the requirements of any job.

Two fundamental properties of insulation materials (for example, rubber, glass, asbestos, and plastic) are insulation resistance and dielectric strength. These are entirely different and distinct properties.

INSULATION RESISTANCE is the resistance to current leakage through and over the surface of insulation materials. Insulation resistance can be measured by means of a megger without damaging the insulation, and information so obtained serves as a useful guide in appraising the general condition of insulation. However, the data obtained in this manner may not give a true picture of the condition of the insulation. Clean-dry insulation having cracks or other faults may show a high value of insulation resistance but would not be suitable for use.

DIELECTRIC STRENGTH is the ability of the insulator to withstand potential difference and is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress. Maximum dielectric strength values can be measured by raising the voltage of a TEST SAMPLE until the insulation breaks down.

Rubber

One of the most common types of insulation is rubber. The voltage that may be applied to a rubber-covered pair of conductors (twisted

pair) is dependent on the thickness and the quality of the rubber covering. Other factors being equal, the thicker the insulation the higher may be the applied voltage. Figure 6-6 shows two types of rubber-covered wire. One is a single, solid conductor, and the other is a 2-conductor cable in which each stranded conductor is covered with rubber insulation. In each case the rubber serves the same purpose—to confine the current to its conductor.

It may be seen from the enlarged cross-sectional view that a thin coating of tin separates the copper conductor from the rubber insulation. If the thin coating of tin were not used, chemical action would take place and the rubber would become soft and gummy where it makes contact with the copper. When small, solid, or stranded conductors are used, a winding of cotton threads is applied between the conductors and the rubber insulation.

Varnished Cambric

Heat is developed when current flows through a wire, and when a large amount of current flows, considerable heat may be developed. The heat can be dissipated if air is circulated freely around the wire. If a cover of insulation is used, the heat is not removed so readily and the temperature may reach a high value.

Rubber is a good insulator at relatively low voltage as long as the temperature remains low. Too much heat will cause even the best grade of rubber insulation to become brittle

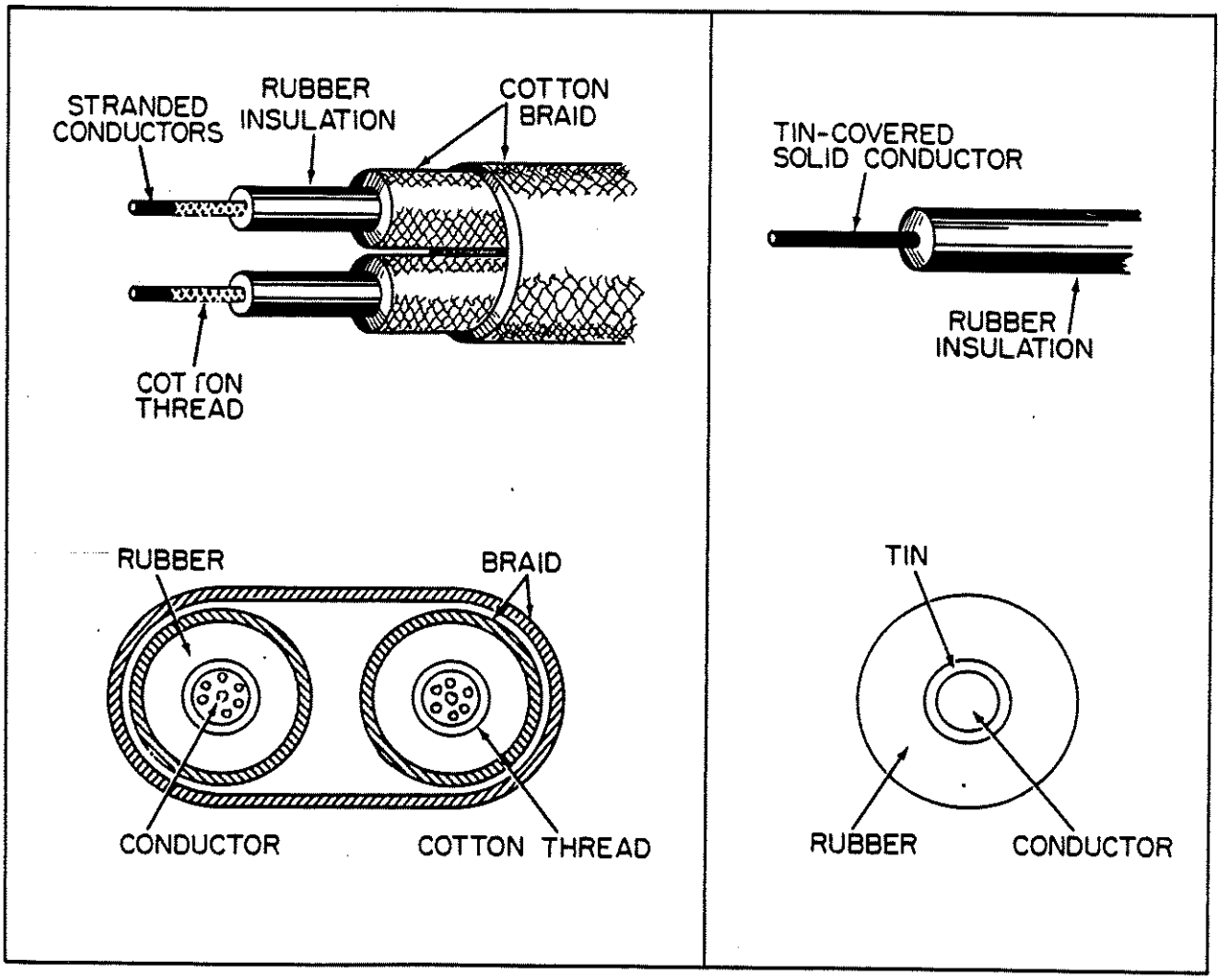


Figure 6-6.—Rubber insulation.

and crack. VARNISHED CAMBRIC insulation will stand much higher temperatures than rubber insulation. Varnished cambric is cotton cloth that has been coated with an insulating varnish. Figure 6-7 shows some of the detail of a cable covered with varnished cambric insulation. The varnished cambric is in tape form and is wound around the conductor in layers. An oily compound is applied between each layer of the tape. This compound prevents water from seeping through the insulation. It also acts as a lubricant between the layers of tape, so they will slide over each other when the cable is bent.

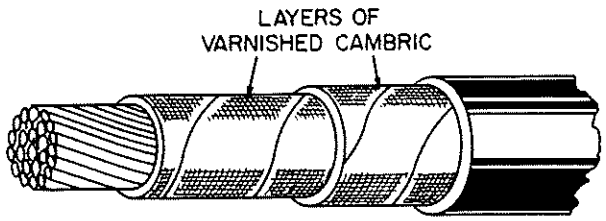


Figure 6-7.—Varnished cambric insulation.

This type of insulation is used on high-voltage conductors associated with switch gear in substations and power houses and other locations subjected to high temperatures. It is also used on high-voltage generator coils and leads, and also on transformer leads because it is unaffected by oils or grease and because it has a high dielectric strength. Varnished cambric and paper insulation for cables are the two types of insulating materials most widely used at voltages above 15,000 volts, but such cables are always lead-covered to keep the moisture out.

Asbestos

Even varnished cambric may break down when the temperature goes above 85° C., (185° F.). When the combined effects of a high ambient (surrounding) temperature and a high internal temperature due to large current flow through the wire makes the total temperature of the wire go above 85° C., ASBESTOS insulation is used.

Asbestos is a good insulation for wires and cables used under very high temperature conditions. It is fire resistant and does not change with age. One type of asbestos-covered wire is shown in figure 6-8. It consists of a stranded copper conductor covered with felted asbestos, which is, in turn, covered with asbestos braid. This type of wire is used in motion-picture projectors, arc lamps, spotlights, heating element leads, and so forth.

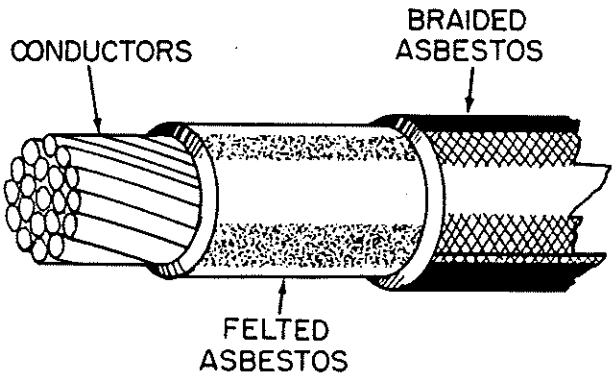


Figure 6-8.—Asbestos insulation.

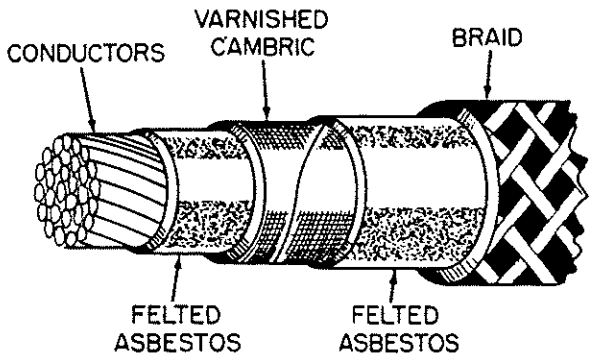


Figure 6-9.—Asbestos and varnished cambric insulation.

Another type of asbestos-covered cable is shown in figure 6-9. It serves as leads for motors and transformers that sometimes must operate in hot, wet locations. The varnished cambric covers the inner layer of felted asbestos and prevents moisture from reaching the innermost layer of asbestos. Asbestos loses its insulating properties when it becomes wet, and will in fact become a conductor. The varnished cambric prevents this from happening because it resists moisture. Although this insulation will withstand some moisture, it should not be used on conductors that may at times be partly immersed in water, unless the insulation is protected with an outer lead sheath.

Paper

Paper has little insulation value alone, but when impregnated with a high grade of mineral oil, it serves as a satisfactory insulation for high-voltage cables. The oil has a high dielectric strength, and tends to prevent breakdown of paper insulation when the paper is thoroughly saturated with it. The thin paper tape is wrapped in many layers around the conductors, and it is then soaked with oil.

The 3-conductor cable shown in figure 6-10 consists of paper insulation on each conductor with a spirally wrapped nonmagnetic metallic tape over the insulation. The space between conductors is filled with a suitable spacer to round out the cable and another nonmagnetic metal tape is used to secure the entire cable, and then a lead sheath is applied over all. This type of cable is used on voltages from 10,000 volts to 35,000 volts.

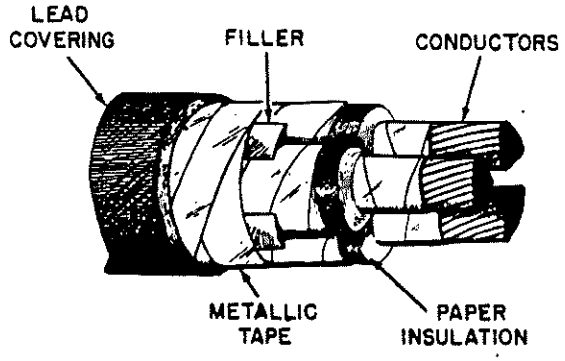


Figure 6-10.—Paper-insulated power cables.

Silk and Cotton

In certain types of circuits—for example, communications circuits—a large number of conductors are needed, perhaps as many as several hundred. Figure 6-11 shows a cable containing many conductors, each insulated from the others by silk and cotton threads.

The use of silk and cotton as insulation keeps the size of the cable small enough to be handled easily. The silk and cotton threads are wrapped around the individual conductors in reverse directions, and the covering is then impregnated with a special wax compound.

Because the insulation in this type of cable is not subjected to high voltage, thin layers of silk and cotton are used.

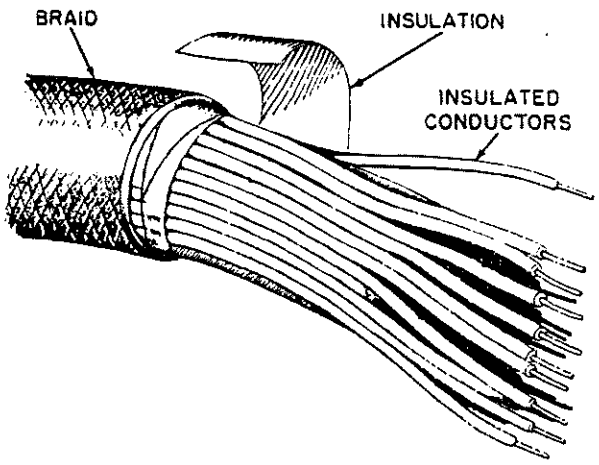


Figure 6-11.—Silk and cotton insulation.

Enamel

The wire used on the coils of meters, relays, small transformers, and so forth, is called MAGNET WIRE. This wire is insulated with an enamel coating. The enamel is a synthetic compound of cellulose acetate (wood pulp and magnesium). In the manufacture, the bare wire is passed through a solution of the hot enamel and then cooled. This process is repeated until the wire acquires from 6 to 10 coatings. Enamel has a higher dielectric strength than rubber for equal thickness. It is not practical for large wires because of the expense and because the insulation is readily fractured when large wires are bent.

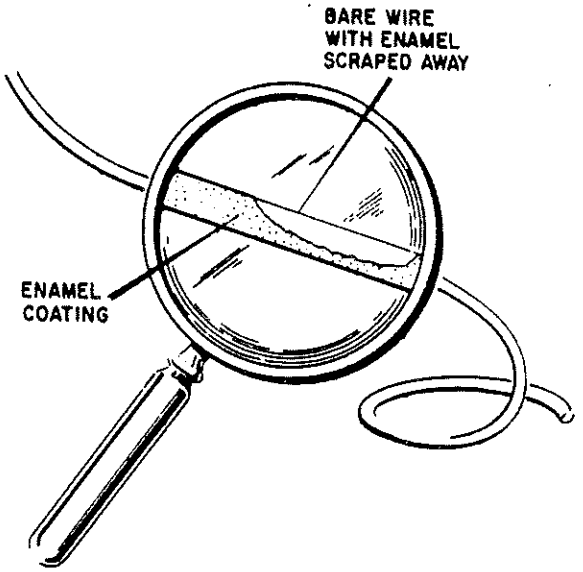


Figure 6-12.—Enamel insulation.

Figure 6-12 shows an enamel-coated wire. Enamel is the thinnest insulating coating that can be applied to wires. Hence, enamel-insulated magnet wire makes smaller coils. Enameled wire is sometimes covered with one or more layers of cotton covering to protect the enamel from nicks, cuts, or abrasions.

CONDUCTOR PROTECTION

Wires and cables are generally subject to abuse. The type and amount of abuse depends on how and where they are installed and the manner in which they are used. Cables buried directly in the ground must resist moisture, chemical action, and abrasion. Wires installed in buildings must be protected against mechanical injury and overloading. Wires strung on crossarms on poles are kept far enough apart so that they do not touch; but snow, ice, and strong winds necessitate the use of conductors having high tensile strength and substantial supporting frame structures.

Generally, except for overload transmission lines, wires or cables are protected by some form of covering. The covering may be some type of insulator like rubber or plastic. Over this an outer covering of fibrous braid may be applied. If conditions require, a metallic outer covering may be used. The type of outer covering used depends on how and where the wire or cable is to be used.

Fibrous Braid

Cotton, linen, silk, rayon, and jute are types of FIBROUS BRAIDS. They are used for outer covering under conditions where the wires or cables are not exposed to heavy mechanical injury. Interior wiring for lights or power is usually done with impregnated cotton, braid-covered, rubber-insulated wire. Generally, the wire will be further protected by a flame-resistant nonmetallic outer covering or by a flexible or rigid conduit.

Figure 6-13 shows a typical building wire. In this instance two braid coverings are used for extra protection. The outer braid is soaked with a compound that resists moisture and flame.

Impregnated cotton braid is used as a covering for outdoor overhead conductors to afford protection against abrasion. For example, the service wires from the transformer secondary mains to the service entrance and also the high-voltage primary mains to the transformer are protected in this manner.

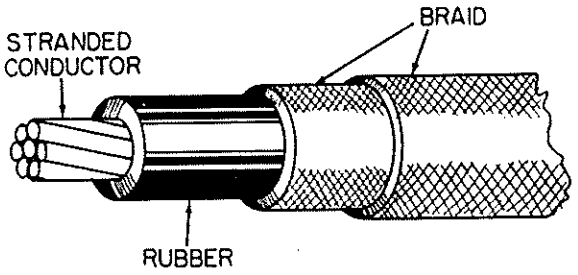


Figure 6-13.—Fibrous braid covering.

Lead Sheath

Subway-type cables or wires that are continually subjected to water must be protected by a watertight cover. This watertight cover is made either of a continuous lead jacket or a rubber sheath molded around the cable.

Figure 6-14 is an example of a lead-sheathed cable used in power work. The cable shown is a stranded 3-conductor type. Each conductor is insulated with rubber and then wrapped with a layer of rubberized tape. The conductors are twisted together and fillers or rope are added to form a rounded core. Over this is wrapped a second layer of tape called the SERVING, and finally the lead sheath is molded around the cable.

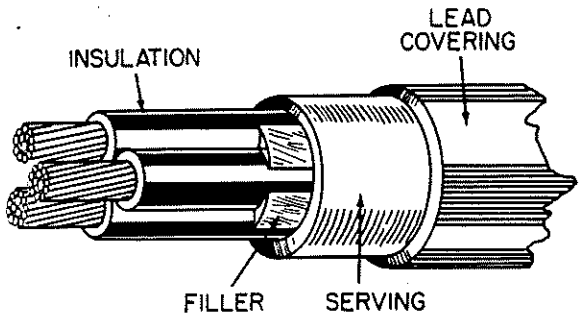


Figure 6-14.—Lead sheathed cable.

Metallic Armor

Metallic armor provides a tough protective covering for wires or cables. The type, thickness, and kind of metal used to make the armor depend on the use of the conductors, the circumstances under which the conductors are to be used, and on the amount of rough treatment that is to be expected.

Four types of metallic armor for cables are shown in figure 6-15.

Wire braid armor is used wherever light, flexible protection is needed. This type of armor is used almost exclusively aboard ship. The individual wires that are woven together to form the metal braid may be made of steel, copper, bronze, or aluminum. Besides mechanical protection, the wire braid also presents a static shield. This is important in radio work aboard ship to prevent interference from stray fields.

When cables are buried directly in the ground, they might be injured from two sources —moisture, and abrasion. They are protected from moisture by a lead sheath, and from abrasion by steel tape or interlocking armor covers. The steel tape covering, as shown in figure 6-15, is wrapped around the cable and then covered with a serving of jute. It is known as Parkway cable. The interlocking armor covering can withstand impacts better than steel tape. Interlocking armor has other uses besides underground work. In wiring the interior of buildings, interlocking armor-covered wire (BX cable) without the lead sheath is frequently used.

Armor wire is the best type of covering to withstand severe wear and tear. Underwater leaded cable usually has an outer armor wire cover.

All wires and cables do not have the same type of protective covering. Some coverings are designed to withstand moisture, others to withstand mechanical strain, and so forth. A cable may have a combination of each type, each doing its own job.

CONDUCTOR SPLICES AND TERMINAL CONNECTIONS

Conductor splices and connections are an essential part of any electric circuit. When

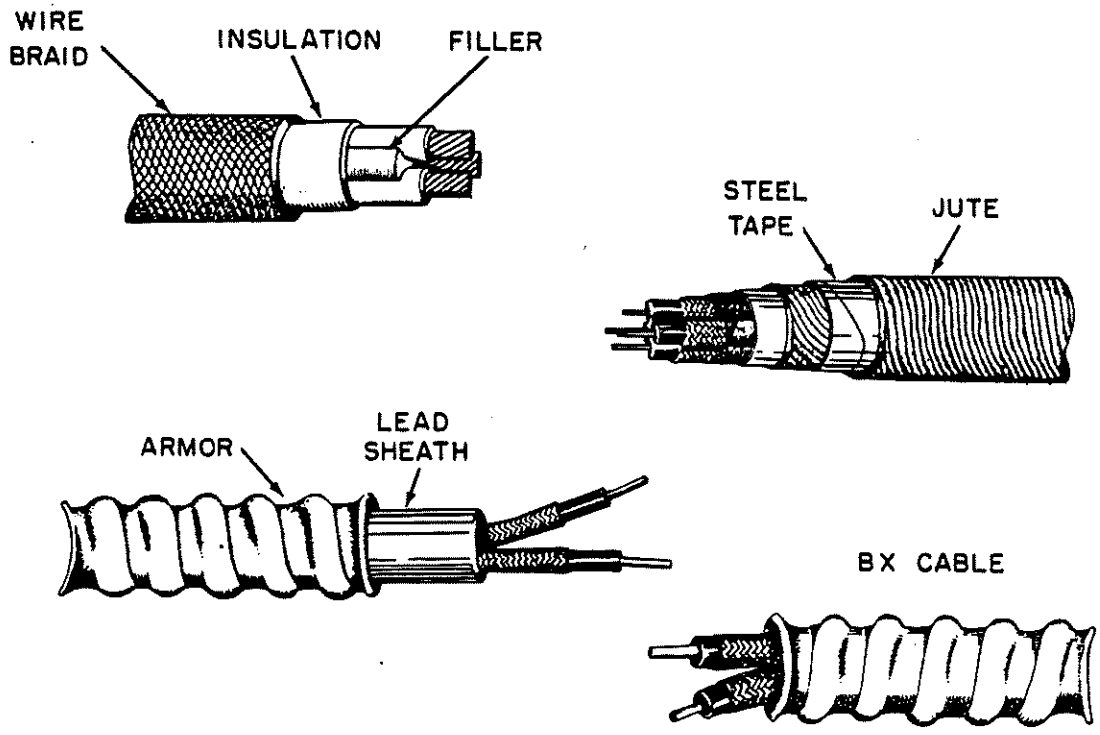


Figure 6-15.—Metallic armor.

conductors join each other, or connect to a load, splices or terminals must be used. It is important that they be properly made, since any electric circuit is only as good as its weakest link. The basic requirement of any splice or connection is that it be both mechanically and electrically as strong as the conductor or device with which it is used. High-quality workmanship and materials must be employed to insure lasting electrical contact, physical strength, and insulation (if required). The most common methods of making splices and connections in electric cables will now be discussed.

Preparing Conductors for Splices and Terminals

The first step in making a splice is preparing the wires or conductor. Insulation must be removed from the end of the conductor and the exposed metal cleaned. In removing the insulation from the wire, a sharp knife is used in much the same manner as in sharpening a pencil. That is, the knife blade is moved at a small angle with the wire to avoid "nicking" the wire. This produces a taper on the cut insulation, as shown in figure 6-16. The insulation may also be removed by using a plier-like hand-operated cable stripper. After the insulation is removed, the bare wire ends should then be scraped bright with the back of a knife blade or rubbed clean with fine sandpaper.

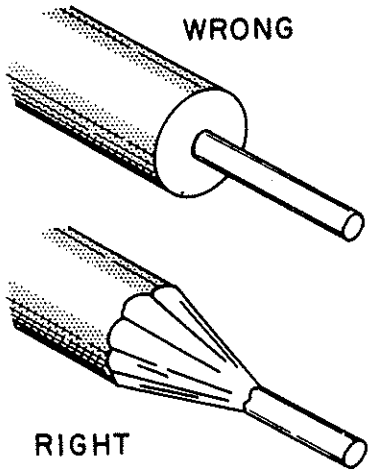


Figure 6-16.—Removing insulation from a wire.

Western Union Splice

Small, solid conductors may be joined together by a simple connection known as the WESTERN UNION SPLICE. In most instances the wires may be twisted together with the fingers and the ends clamped into position with a pair of pliers.

Figure 6-17 shows the steps in making a Western Union splice. First, the wires are prepared for splicing by removing sufficient insulation and cleaning the conductor. Next, the wires are brought to a crossed position and a long twist or bend is made in each wire. Then one of the wire ends is wrapped four of five times around the straight portion of the wire. The other end wire is wrapped in a similar manner. Finally, the ends of the wires should be pressed down as close as possible to the straight portion of the wire. This prevents the sharp ends from puncturing the tape covering that is wrapped over the splice.

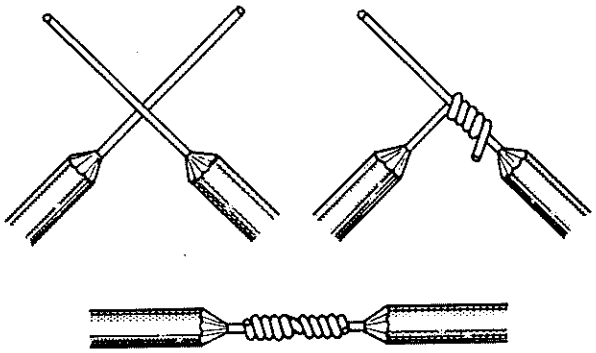
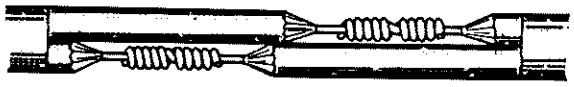


Figure 6-17.—Western Union splice.

Staggered Splice

Joining small, multiconductor cables together presents somewhat of a problem. Each conductor must be spliced and taped; and if the splices are directly opposite each other, the overall size of the joint becomes large and bulky. A smoother and less bulky joint may be made by staggering the splices.

Figure 6-18 shows how a 2-conductor cable is joined to a similar cable by means of the staggered splice. Care should be exercised to ensure that a short wire is connected to a long wire, and that the sharp ends are clamped firmly down on the conductor.



STAGGERED SPLICE

Figure 6-18.—Staggered splice.

Rattail Joint

Wiring that is installed in buildings is usually placed inside long lengths of steel pipe (conduit). Whenever branch circuits are required, junction or pull boxes are inserted in the conduit. One type of splice that is used for branch circuits is the rattail joint shown in figure 6-19.

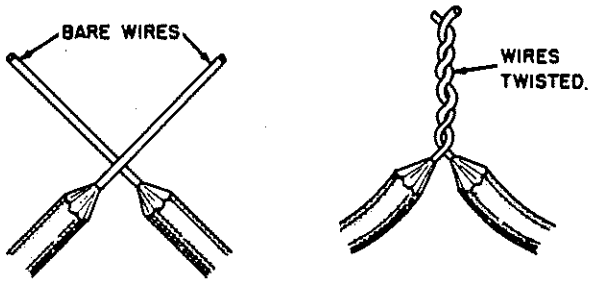


Figure 6-19.—Rattail joint.

The ends of the conductors to be joined are stripped of insulation. The wires are then twisted to form the rattail effect.

Fixture Joint

A fixture joint is used to connect a light fixture to the branch circuit of an electrical system where the fixture wire is smaller in diameter than the branch wire. Like the rattail joint, it will not stand much mechanical strain.

The first step is to remove the insulation from the wires to be joined. Figure 6-20 shows the steps in making a fixture joint.

After the wires are prepared, the fixture wire is wrapped a few times around the branch wire, as shown in the figure. The wires are not twisted, as in the rattail joint. The end of the branch wire is then bent over the completed turns. The remainder of the bare fixture wire is then wrapped over the bent branch wire. Soldering and taping completes the job.

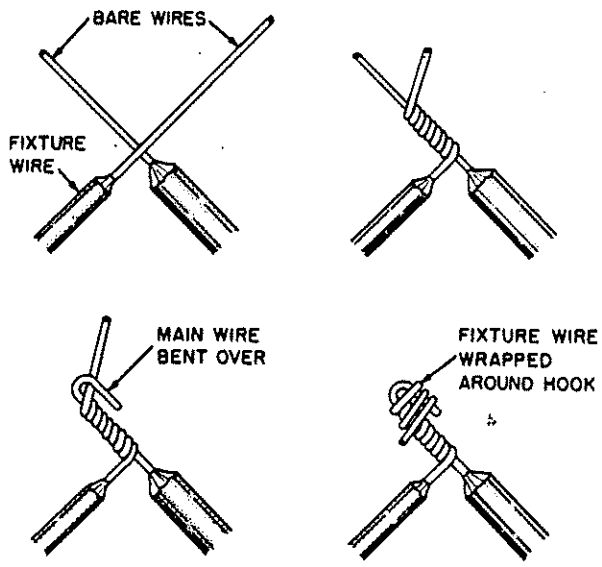
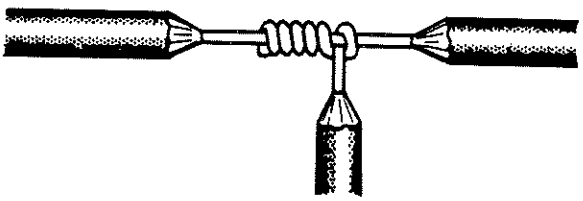


Figure 6-20.—Fixture joint.

Knotted Tap Joint

All of the splices considered up to this point are known as BUTTED splices. Each was made by joining the FREE ends of the conductors together. Sometimes, however, it is necessary to join a conductor to a CONTINUOUS wire, and such a junction is called a TAP joint.

The main wire, to which the branch wire is to be tapped, has about one inch of insulation removed. The branch wire is stripped of about three inches of insulation. The steps in making the tap are shown in figure 6-21.



KNOTTED TAP JOINT

Figure 6-21.—Knotted tap joint.

The branch wire is crossed over the main wire, as shown in the figure, with about three-fourths of the bare portion of the branch wire

extending above the main wire. The end of the branch wire is bent over the main wire, brought under the main wire, around the branch wire, and then over the main wire to form a knot. It is then wrapped around the main conductor in short, tight turns and the end is trimmed off.

The knotted tap is used where the splice is subject to strain or slip. When there is no mechanical strain, the knot may be eliminated.

SOLDERING EQUIPMENT

The various splices and joints commonly used are not completed until they are properly soldered and insulated.

Solder

Solder is a metallic alloy with a low melting point; it is used to join metallic surfaces. Solder used in electrical work comes in two forms. —solid solder bars, and the rosin core type, resembling wire wound on spools. Figure 6-22 illustrates the two types.

The rosin core type solder is most commonly used. The rosin core of the solder, when melted, flows on the surfaces of the splice or joint, preventing their contact with air and thus preventing oxidation. Without oxidation, the solder and surfaces will cohere strongly.

Soldering Iron

The soldering iron is a handtool that is used to heat the wire splice or joint to a temperature that will cause the solder to melt and flow freely over the splice or joint. Electric soldering irons are rated in watts, from 25 to 500. The size of the conductors being soldered will determine the size of soldering iron to be used. All high quality irons operate in a temperature range of 500° to 600° F. Even the little 25-watt midget iron produces this temperature. The important difference in iron sizes is not temperature, but the capacity of the iron

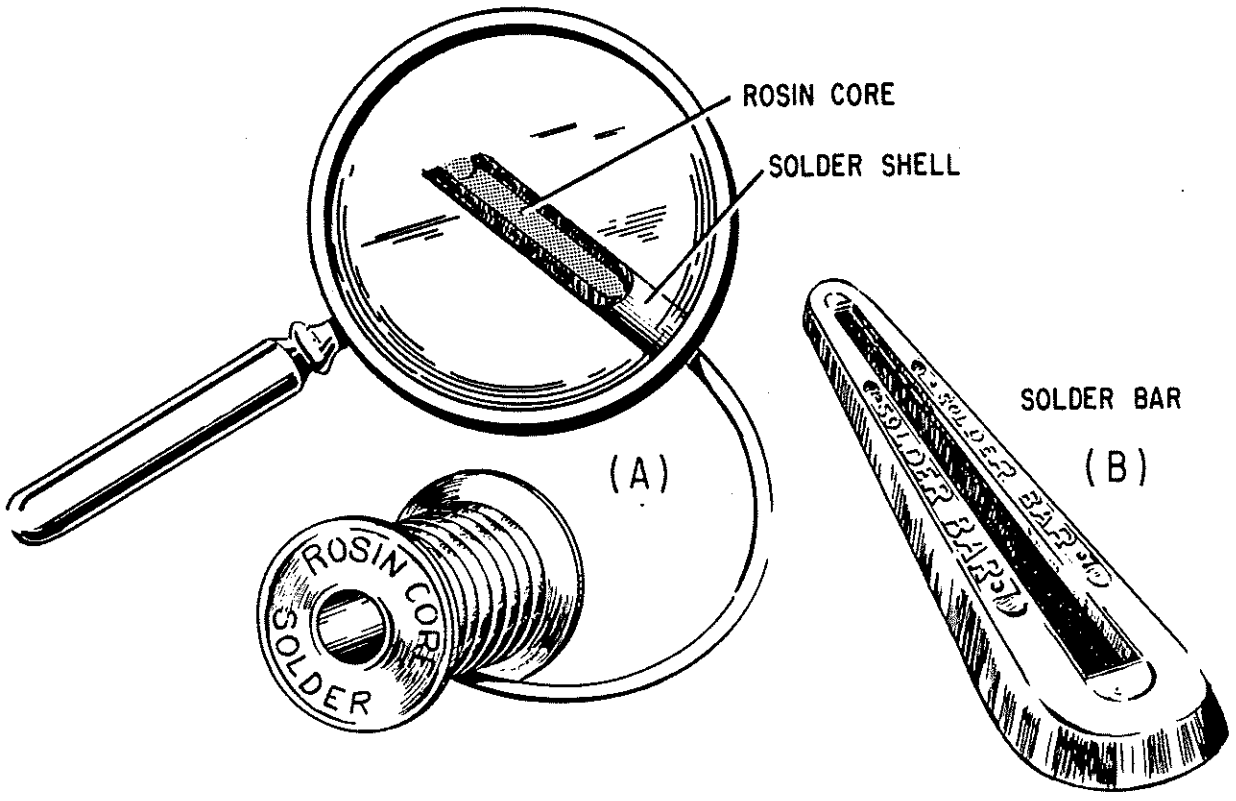


Figure 6-22.—Solder: (A) Rosin core; (B) solid bars.

to generate and maintain a satisfactory soldering temperature while giving up heat to the joint to be soldered.

Some irons have built-in thermostats. Others are provided with thermostatically controlled stands. One type of iron is equipped with several different tips that range from 1/4 inch to 1/2 inch is size (diameter) and are of various shapes. This feature makes the iron adaptable to a variety of jobs. Figure 6-23 shows several different type soldering irons.

ELECTRIC HEATING ELEMENT SOLDERING IRON

Figure 6-23 (A) shows three common sizes of the electric heating element soldering iron. This is the most commonly used type iron. A cylindrical electric heating element is mounted in its body. About half of the copper tip is inserted and secured within the cylindrical element, obtaining heat by physical contact. Heat is conducted to the protruding half, to be used in melting solder.

INDUCTION-TYPE SOLDERING IRON

This soldering iron (most often referred to as "soldering gun") is shown in figure 6-23 (B). It contains a stepdown transformer in its body. The transformer secondary output current flows through the tip, causing it to heat. The tip heats only when the trigger is depressed, and then very rapidly. This type iron affords easy access to cramped quarters, because of its small tip. It usually has a small light which is focused on the tip working area. The soldering tip is replaceable.

ELECTRIC RESISTANCE SOLDERING IRON

This iron is shown in figure 6-23 (C). When the contact jaws are clamped on the work, current flows between the jaws through the work. The contact resistance causes heating, thus melting the solder.

TORCH-HEATED SOLDERING IRON

As shown in figure 6-23 (D), this type iron is heated directly by a blowtorch or other heat source. It is then held against the soldering work to transfer its heat. After cooling to an unusable temperature, it is reheated. This iron is usually used where electric power is not available and an open flame is permissible.

Care of Soldering Iron

Soldering irons require more care in both use and maintenance than most handtools. A typical electric iron has a heating element, a power cord, a wooden handle, and a copper tip.

The copper tip generally requires the most care and maintenance. Also, to prevent damage to the heating element, the iron should not be subjected to heavy mechanical abuse. For instance, if the iron is dropped, or used as a hammer, the heating element may be broken or shorted. Always make certain that the cord does not come in contact with the iron tip, where it can be burned.

The copper tip should be removed occasionally to permit cleaning away the oxide scale which forms between the tip and metal housing. Removal of this oxide increases the heating efficiency of the iron.

Before a soldering iron can be used for soldering, the pointed end of the copper tip must be tinned. Unless the tip is tinned the iron will not readily transfer heat from the copper tip to the connection to be soldered. Tinning the end of the copper means covering it with a thin coating of solder. After heating, all of the tip except the tinned portion becomes covered with an oxide film. This film does not readily conduct heat. Only the tinned portion of the tip will give off enough heat to melt solder readily. An iron which needs tinning does not produce satisfactory results when making solder connections. After an iron has been used for a period of time, the solder on the tip burns off and the iron needs retinning.

The action of the heat and solder causes pitting and corroding of the tip. Consequently, it not only needs retinning occasionally, but also needs occasional reshaping. Tips usually either have a 4-sided taper point or a 2-sided chisel point. Regardless of the tip size or shape, the same tinning procedure is used.

To reshape the tip, first remove it from the iron, either by unscrewing it from the housing or loosening a setscrew, depending on the type of iron. Place the tip in a vise with the point in such a position that the side to be tinned can be filed. Do not tighten the vise too tightly, as the copper tip is soft and bends easily. Using flat strokes, file the sides of the point until all of

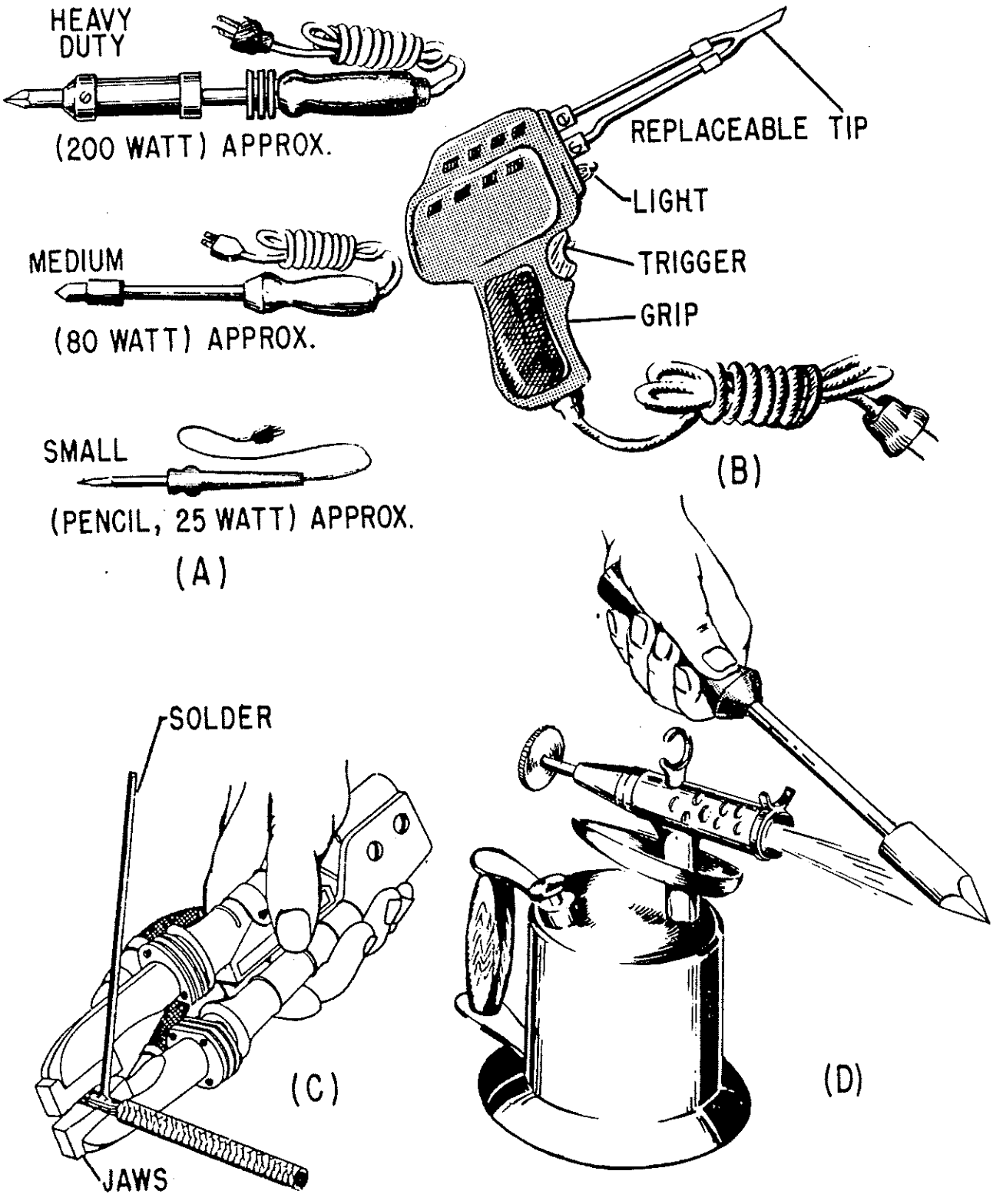


Figure 6-23.—Soldering irons.

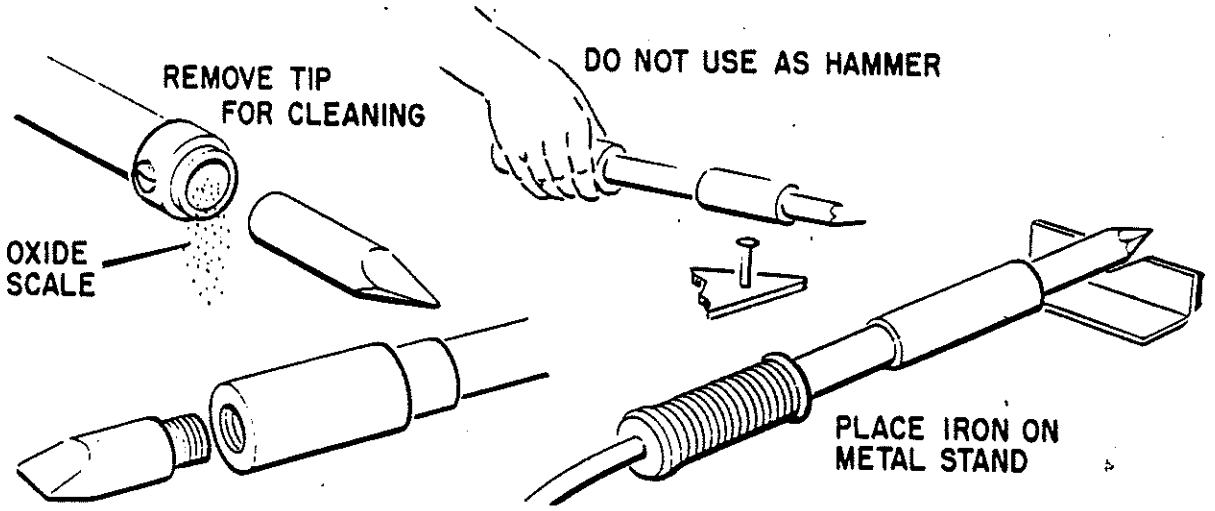


Figure 6-24.—Caring for the soldering iron.

the pits, oxide, and old tinning are removed. Always file the tip to the original taper, making certain that you do not round off the sides of the point.

Replace the filed tip in the iron housing. Holding the iron with the tip upward, plug the cord into a power outlet. As the iron heats, touch rosin core solder to the cleaned sides of the tip at intervals until the iron first begins to melt the solder. Then quickly melt solder onto all of the cleaned portion of the tip, applying as much solder as will melt onto each side. With a dry cloth or piece of steel wool, lightly brush the excess solder from the tinned sides of the tip. The iron is now ready to use for soldering. Heated irons, when not in actual use, should be placed on a metal iron rest or some other appropriate holder.

To solder an electrical connection, the tinned portion of the iron tip is held flat against the connection, as shown in figure 6-25. Touch solder to the connection until the entire connection is covered with molten solder. Remove the solder, but continue to apply heat for a moment; then remove the iron and allow the solder to harden. The solder should always be melted by the heated wire and not by the iron. Melting the solder onto the iron and then transferring it to the connection often results in a cold solder joint, with the solder not actually holding to the wire or connection. Only enough solder to fill all crevices and spaces in the joint should be used.

TAPING A SPLICE

The final step in completing a splice or joint is the placing of insulation over the bare wire. The insulation should be of the same basic substance as the original insulation. Usually a rubber splicing compound is used.

Rubber Tape

Latex (rubber) tape is a splicing compound. It is used where the original insulation was rubber. The tape is applied to the splice with a light tension so that each layer presses tightly against the one underneath it. This pressure causes the rubber tape to blend into a solid mass. When the application is completed, an insulation similar to the original has been restored.

Between each layer of latex tape, when it is in roll form, there is a layer of paper or treated cloth. This layer prevents the latex from fusing while still on the roll. The paper or cloth is peeled off and discarded before the tape is applied to the splice.

Figure 6-26 shows the correct way to cover a splice with rubber insulation. The rubber splicing tape should be applied smoothly and under tension so that there will be no air spaces between the layers. In putting on the first layer, start near the middle of the joint instead of the end. The diameter of the completed insulated joint should be somewhat greater that

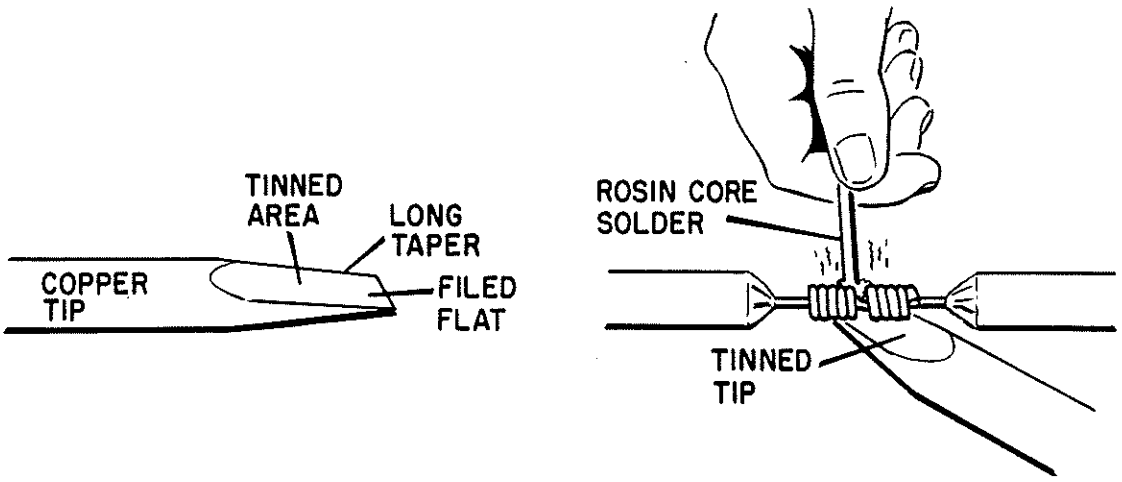


Figure 6-25.—Soldering a splice.

the overall diameter of the original cable, including the insulation.

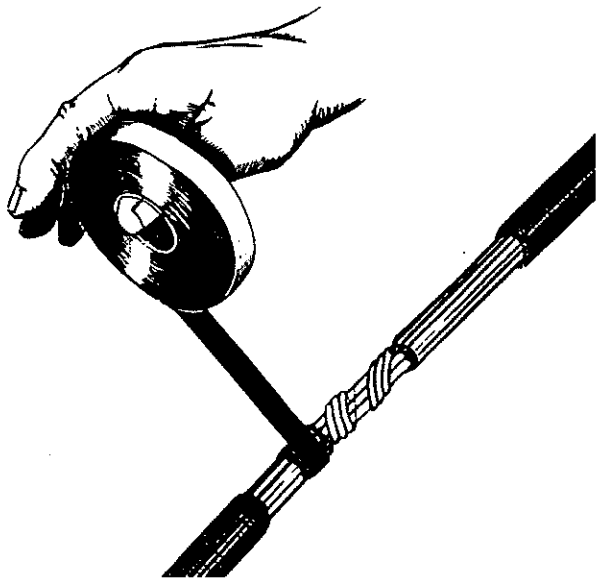


Figure 6-26.—Applying rubber tape.

Friction Tape

Putting rubber tape over the splice means that the insulation has been restored to a great degree. It is also necessary to restore the protective covering. Friction tape is used for this purpose; it also affords a minor degree of electrical insulation.

Friction tape is a cotton cloth that has been treated with a sticky rubber compound. It comes in rolls similar to rubber tape except that no paper or cloth separator is used. Friction tape is applied like rubber tape; however, it does not stretch.

The friction tape should be started slightly back on the original braid covering. Wind the tape so that each turn overlaps the one before it; and extend the tape over onto the braid covering at the other end of the splice. From this point a second layer is wound back along the splice until the original starting point is reached. Cutting the tape and firmly pressing down the end complete the job. When proper care is taken, the splice can take as much abuse as the rest of the wire.

Weatherproof wire has no rubber insulation, just a braid covering. In that case, no rubber tape is necessary, only friction tape need be used.

Plastic Electrical Tape

Plastic electrical tape has come into wide use in recent years. It has certain advantages over rubber and friction tape. For example, it will withstand higher voltages for a given thickness. Single thin layers of certain commercially available plastic tape will stand several thousand volts without breaking down. However, to provide an extra margin of safety several layers are usually wound over the splice. Because the tape is very thin, the extra

layers add only a very small amount of bulk; but at the same time the added protection, normally furnished by friction tape, is provided by the additional layers of plastic tape. In the choice of plastic tape, the factor of expense must be balanced against the other factors involved.

Plastic electric tape normally has a certain amount of stretch so that it easily conforms to the contour of the splice without adding unnecessary bulk. The lack of bulkiness is especially important in some junction boxes where space is at a premium.

For high temperatures—for example, above 175° F.—a special type of tape backed with glass cloth is used.

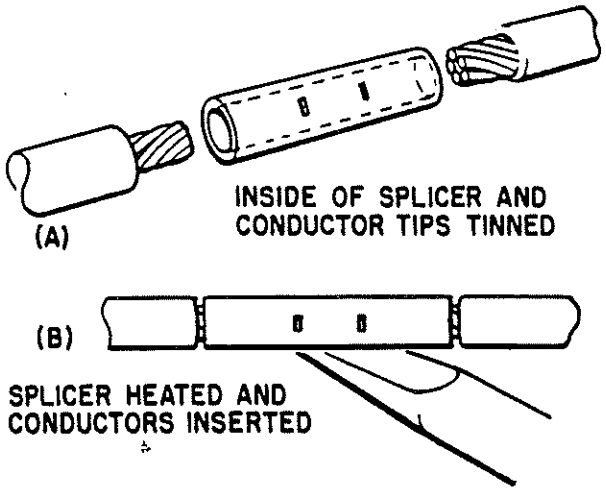


Figure 6-27.—Steps in using solder splicer.

SOLDER CONNECTORS

In some cases, splices and joints cannot readily be made by twisting and soldering conductors. For instance, it would be quite difficult to twist conductors together neatly if each consisted of many small strands. Stranded conductors are usually spliced by using special hardware designed for that purpose. Some of these devices use solder, while others do not.

Solder Splicers

The solder-type splicer is essentially a short piece of metal tube. Its inside diameter is just large enough to allow the tip of a stranded conductor to be inserted in either end, after the conductor tip has been stripped of insulation. This type of splicer is shown in figure 6-27.

The splicer is first heated and filled with solder. While still molten, the solder is then poured out, leaving the inner surfaces tinned. When the conductor tips are stripped, the length of exposed strands should be long enough so that the insulation butts against the splicer when the conductors are tinned and fully inserted. (See fig. 6-27 (B).) When heat is applied to the connection and the solder melts, excess solder will be squeezed out through the vents. This must be cleaned away. After the splice has cooled, insulating material must be wrapped or tied over the joint.

Solder Terminal Lugs

In addition to being joined or spliced to one another, conducts are often connected to other objects, such as motors and switches. Since this is where a length of conductor ends (terminates), such connections are referred to as terminal points. In some cases, it is allowable to bend the end of the conductor into a small "eye" and put it around a terminal binding post. Where a mounting screw is used, the screw is passed through the eye. The conductor tip which forms the eye should be bent as

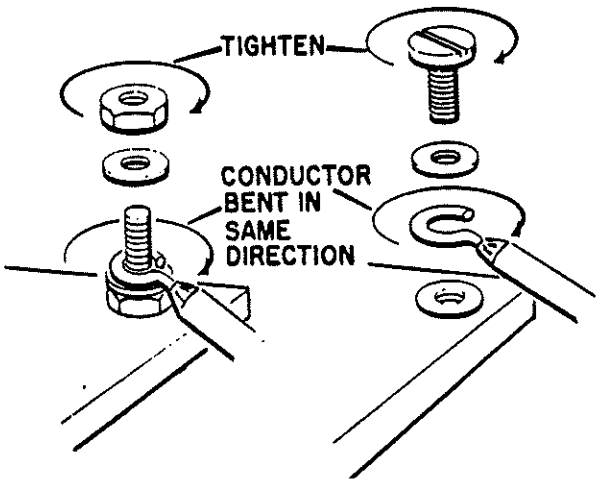


Figure 6-28.—Conductor terminal connection.

shown in figure 6-28. Note that when the screw or binding nut is tightened, it also tends to tighten the conductor eye.

This method of connection is sometimes not desirable. When design requirements are more rigid, terminal connections are made by using special hardware devices called terminal lugs. There are terminal lugs of many different sizes and shapes, but all are essentially the same as the type shown in figure 6-29.

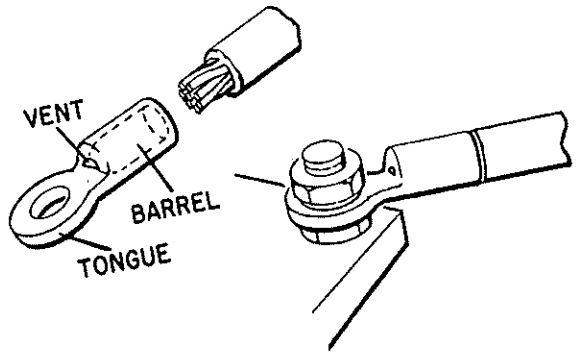


Figure 6-29.—Solder-type terminal lug.

Each type of lug has a barrel (sleeve) which is wedged, crimped, or soldered to its conductor. There is also a tongue with a hold or slot in it to receive the terminal post or screw. When mounting a solder-type terminal lug to a conductor, first tin the inside of the barrel. The conductor tip is stripped and also tinned, then inserted in the preheated lug. When mounted, the conductor insulation should butt against the lug barrel, so that there is no exposed conductor.

SOLDERLESS CONNECTORS

Splicers and terminal lugs which do not require solder are more widely used than those which do require solder. Solderless connectors are attached to their conductors by means of several different devices, but the principle of each is essentially the same. They are all squeezed (crimped) tightly onto their conductors. They afford adequate electrical contact, plus great mechanical strength. In addition, solderless connectors are easier to mount correctly because they are free from the most common problems of solder connector mounting; namely, cold solder joints, burned insulation, and so forth.

Solderless connectors are made in a great variety of sizes and shapes, and for many different purposes. Only a few are discussed here.

Solderless Splicers

Three of the most common type solderless splicers, classified according to their methods of mounting, are the split-sleeve, split-tapered-sleeve, and crimp-on splicers.

SPLIT-SLEEVE SPLICER

A split-sleeve splicer is shown in figure 6-30. To connect this splicer to its conductor, the stripped conductor tip is first inserted between the split-sleeve jaws. Using a tool designed for that purpose, the slide ring is forced toward the end of the sleeve. The sleeve jaws are closed tightly on the conductor, and the slide ring holds them securely.

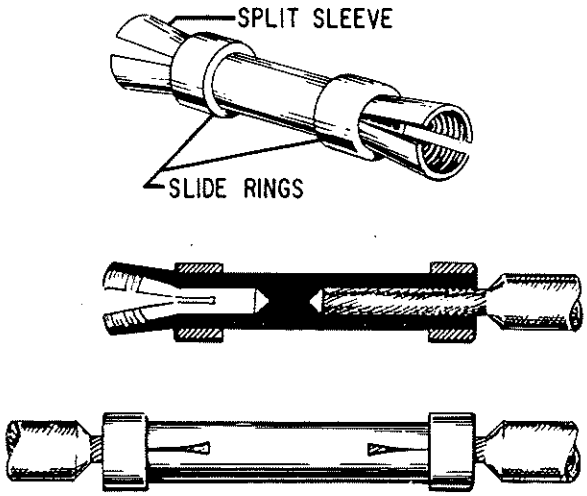


Figure 6-30.—Split-sleeve splicer.

SPLIT-TAPERED-SLEEVE SPLICER

A cross-sectional view of a split-tapered-sleeve splicer is shown in figure 6-31 (A). To mount this type of splicer, the conductor is stripped and inserted in the split-tapered sleeve. The threaded sleeve is turned or screwed into the tapered bore of the body. As the sleeve is turned in, the split segments are squeezed tightly around the conductor by the narrowing bore. The finished splice (fig. 6-31 (B)), must be covered with insulation.

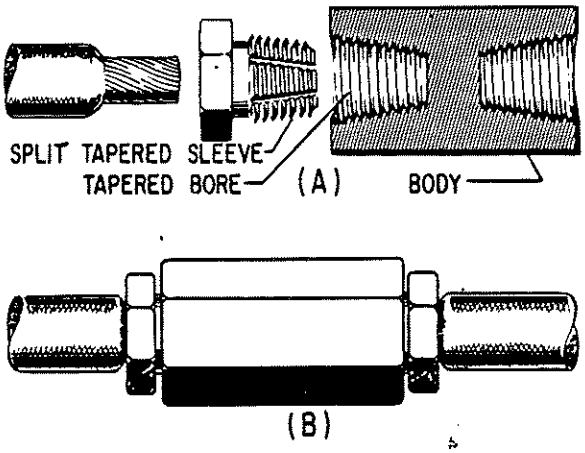


Figure 6-31.–Split-tapered-sleeve splice.

CRIMP-ON SPLICER

The crimp-on splicer (fig. 6-32) is the simplest of the splicers discussed. The type shown is preinsulated, though uninsulated types are manufactured. These splicers are mounted with a special plier-like hand-crimping tool designed for that purpose. The stripped conductor tips are inserted in the splicer, which is then squeezed tightly closed. The insulating sleeve grips the outer insulated conductor, and the metallic internal splicer grips the bare conductor strands.

Solderless Terminal Lugs

Solderless terminal lugs are used more widely than solder terminal lugs. They afford adequate electrical contact, plus great mechanical strength. In addition, solderless lugs are easier to attach correctly, because they are free from the most common problems of solder terminal lugs; namely, cold solder joints, burned insulation, and so forth. There are many sizes and shapes of these lugs, each intended for a different type of service of conductor size. Only a few are discussed here.

These are classified according to their method of mounting. They are the split-tapered-sleeve (wedge-type), split-tapered-sleeve (threaded-type), and crimp-on.

SPLIT-TAPERED-SLEEVE TERMINAL LUG (WEDGE)

This type lug is shown in figure 6-33. It is commonly referred to as a "wedge-on," because of the manner in which it is secured to a conductor. The stripped conductor is inserted through the hole in the split sleeve. When the sleeve is forced or "wedged" down into the barrel, its tapered segments are squeezed tightly around the conductor.

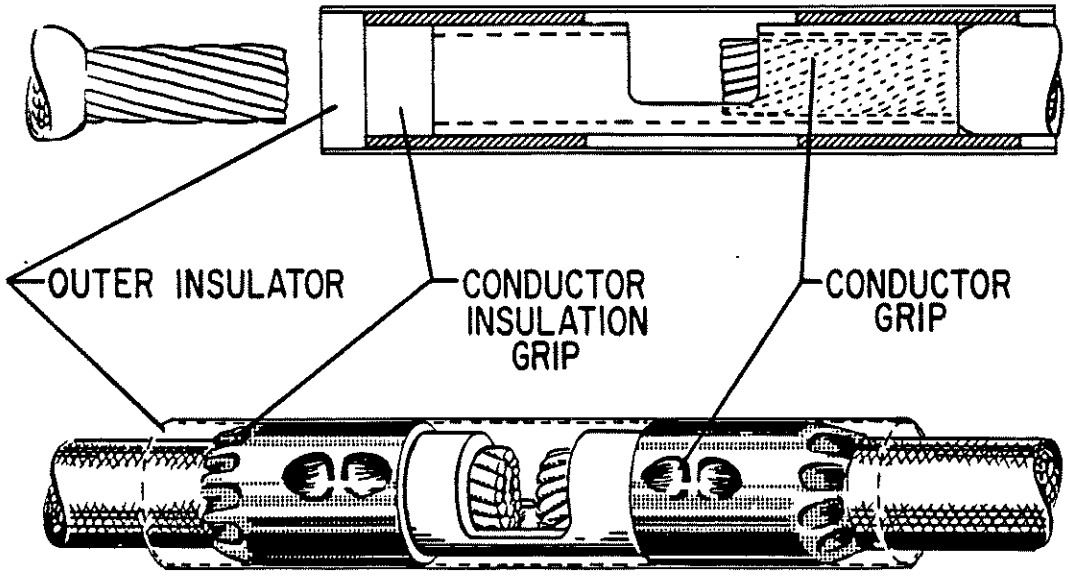


Figure 6-32.–Crimp-on splicer.

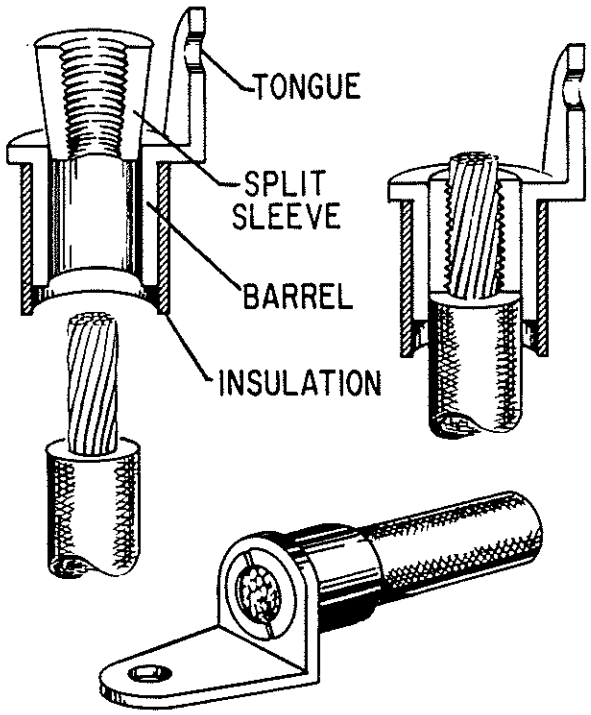


Figure 6-33.—Split-tapered-sleeve terminal lug (wedge type).

SPLIT-TAPERED-SLEEVE TERMINAL LUG (THREADED)

This lug (fig. 6-34) is attached to a conductor in exactly the same manner as a split-sleeve splicer. The segments of the threaded split sleeve squeezes tightly around the conductor as it is turned into the tapered bore of the barrel. For this reason, the lug is commonly referred to as a "screw-wedge."

CRIMP-ON TERMINAL LUG

The crimp-on lug is shown in figure 6-35. This lug is simply squeezed or "crimped" tightly onto a conductor. This is done by using the same tool used with the crimp-on splicer. The lug shown is preinsulated, but uninsulated types are manufactured. When mounted, both the conductor and its insulation are gripped by the lug.

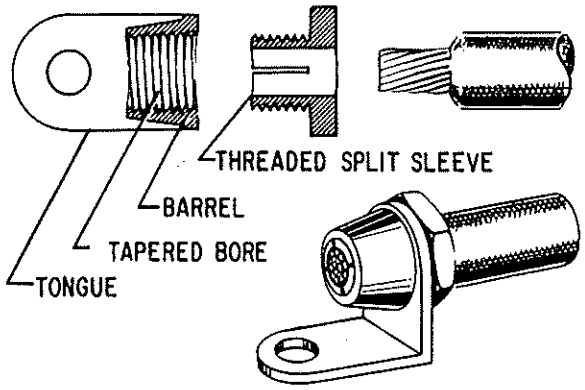


Figure 6-34.—Split-tapered-sleeve terminal lug (threaded).

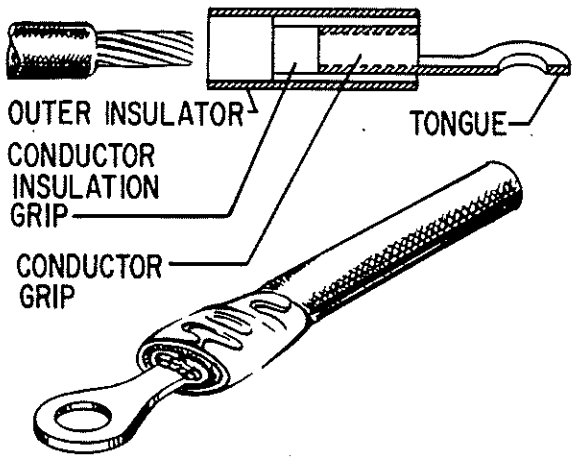


Figure 6-35.—Crimp-on terminal lug.

QUIZ

1. A mil is what part of an inch?
   a. 1/10
   b. 1/100
   c. 1/1000
   d. 1/1,000,000

2. The discharge (electrical leakage) that might occur from a wire carrying a high potential is called
   a. arcing
   b. sparking
   c. static discharge
   d. corona

3. Bare wire ends are spliced by the
   a. western union method
   b. rat-tail joint method
   c. fixture joint method
   d. all of the above
4. What is a unit conductor called that has a length of one foot and a cross-sectional area of one circular mil?
   a. Square mil
   b. Circular mil
   c. Circular mil foot
   d. Square mil foot
5. The induction-type soldering iron is commonly known as the
   a. soldering copper
   b. pencil iron
   c. soldering gun
   d. resistance gun
6. All good quality soldering irons operate at what temperature?
   a. 400 - 500° F.
   b. 500 - 600° F.
   c. 600 - 700° F.
   d. 300 - 600° F.
7. A No. 12 wire has a diameter of 80.81 mils. What is the area in circular mils?
   a. 6,530 cm.
   b. 5,630 cm.
   c. 4,530 cm.
   d. 3,560 cm.
8. Dielectric strength is the
   a. opposite of potential difference
   b. ability of a conductor to carry large amounts of current
   c. ability of an insulator to withstand a potential difference
   d. strength of a magnetic field
9. To readily transfer the heat from the soldering iron tip, it first should be
   a. tinned with solder
   b. allowed to form an oxide film
   c. cleaned with carbon tet
   d. allowed to heat for 25 minutes
10. A No. 12 wire has a diameter of 80.81 mils. What is the area in square mils?
    a. 2,516.8 square mils
    b. 5,128.6 square mils
    c. 6,530 square mils
    d. 8,512.6 square mils
11. Varnished cambric insulation is used to cover conductors carrying voltages above
    a. 1,000 volts
    b. 1,500 volts
    c. 15,000 volts
    d. 5,000 volts
12. The solder splicer is used to
    a. prevent the waste of rosin core solder
    b. connect together small lengths of solder
    c. connect two conductors together
    d. none of the above
13. The conductance of a conductor is the ease with which current will flow through it. It is measured in
    a. ohms
    b. mhos
    c. henrys
    d. amperes
14. Asbestos insulation loses its insulating properties when it becomes
    a. overaged
    b. overheated
    c. used over a long period of time
    d. wet
15. How are solderless connectors installed on conductors?
    a. Bolted on
    b. Chemical compound
    c. Crimped on
    d. All of the above
16. The factor(s) governing the selection of wire size is/are
    a. (I^2R loss) in the line
    b. (IR drop) in the line
    c. current-carrying ability of the line
    d. all of the above
17. Enamel insulated conductors are usually called
    a. magnet wire
    b. high voltage wire
    c. low voltage wire
    d. transmission lines
18. The advantage of solderless connectors over soldered type connectors is that they are
    a. mechanically stronger
    b. easier to install
    c. free of corrosion
    d. all of the above
19. The basic requirement of any splice is that it be
    a. soldered
    b. mechanically and electrically as strong as the conductor that is spliced
    c. made with a splicer
    d. taped
20. The type of tape that is used for electrical circuits having a temperature of 175° F. or above is
    a. glass cloth
    b. plastic
    c. synthetic rubber compound
    d. impregnated cloth

CHAPTER 7

ELECTROMAGNETISM AND MAGNETIC CIRCUITS

The fundamental theories concerning simple magnets and magnetism were discussed in chapter 1 of this course. Those discussions dealt mainly with forms of magnetism that were not related directly to electricity—permanent magnets for instance. Only brief mention was made of those forms of magnetism having direct relation to electricity (such as "producing electricity with magnetism"). This chapter resumes the study of magnetism where chapter 1 left off. Therefore, it may be necessary for you to review parts of chapter 1 from time to time. This chapter begins the more advanced study of MAGNETISM AS IT IS AFFECTED BY ELECTRIC CURRENT FLOW, and the closely related study of ELECTRICITY AS IT IS AFFECTED BY MAGNETISM. This general subject area is most often referred to as ELECTROMAGNETISM.

Magnetism and basic electricity are so closely related that one cannot be studied at length without involving the other. This close fundamental relationship will be continually borne out in other chapters of this course, such as in the study of generators, transformers, and motors. You will become familiar with many of the most general relationships between magnetism and electricity, such as the following:

1. Electric current flow will ALWAYS produce some form of magnetism.

2. Magnetism is by far the most commonly used means for producing or using electricity.

3. The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

Magnetic Field Around a Current-Carrying Conductor

In 1819 Hans Christian Oersted, a Danish physicist, found that a definite relation exists between magnetism and electricity. He discovered that an electric current is accompanied by certain magnetic effects and that these effects obey definite laws. If a compass is placed in the vicinity of a current-carrying conductor, the needle alines itself at right angles to the conductor, thus indicating the presence of a magnetic force. The presence of this force can be demonstrated by passing an electric current through a vertical conductor which passes through a horizontal piece of cardboard, as illustrated in figure 7-1. The magnitude and direction of the force are determined by setting a compass at various points on the cardboard and noting the deflection.

The direction of the force is assumed to be the direction the north pole of the compass points. These deflections show that a magnetic field exists in circular form around the conductor. When the current flows upward, the field direction is clockwise, as viewed from the top, but if the polarity of the supply is reversed so that the current flows downward, the direction of the field is counterclockwise.

The relation between the direction of the magnetic lines of force around a conductor and the direction of current flow along the conductor may be determined by means of the LEFT-HAND RULE FOR A CONDUCTOR. If the conductor is grasped in the left hand with the thumb extended in the direction of electron flow (- to +), the fingers will point in the direction of the magnetic lines of force. This is the same direction in which the north pole of a compass would point if the compass was placed in the magnetic field.

Arrows generally are used in electric diagrams to denote the direction of current flow along the length of wire. Where cross sections of wire are shown, a special view of the arrow

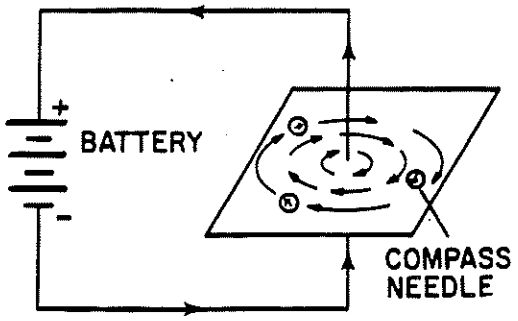


Figure 7-1.—Magnetic field around a current-carrying conductor.

is used. A cross-sectional view of a conductor that is carrying current toward the observer is illustrated in figure 7-2 (A). The direction of current is indicated by a dot, which represents the head of the arrow. A conductor that is carrying current away from the observer is illustrated in figure 7-2 (B). The direction of current is indicated by a cross, which represents the tail of the arrow.

When two parallel conductors carry current in the same direction, the magnetic fields tend to encircle both conductors, drawing them together with a force of attraction, as shown in figure 7-3 (A). Two parallel conductors carrying currents in opposite directions are shown in figure 7-3 (B). The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force are crowded together in the space between the wires, and tend to push the wires apart. Therefore, two parallel adjacent conductors carrying currents in the same direction attract each other and two parallel conductors carrying currents in opposite directions repel each other.

Magnetic Field of a Coil

The magnetic field around a current-carrying wire exists at all points along its length. The field consists of concentric circles in a plane perpendicular to the wire. (See fig. 7-1.) When this straight wire is wound around a core, as shown in figure 7-4 (A), it becomes a coil and the magnetic field assumes a different shape. Part (A) is a partial cutaway view which shows the construction of a simple coil. Part (B) is a complete cross-sectional view of the same coil. The two ends of the coil are identified as *a* and *b*. When current is passed through the coiled conductor, as indicated, the magnetic field of each turn of wire links with the fields of adjacent turns, as explained in connection with figure 7-3 (A). The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil will be a north pole and the other end will be a south pole.

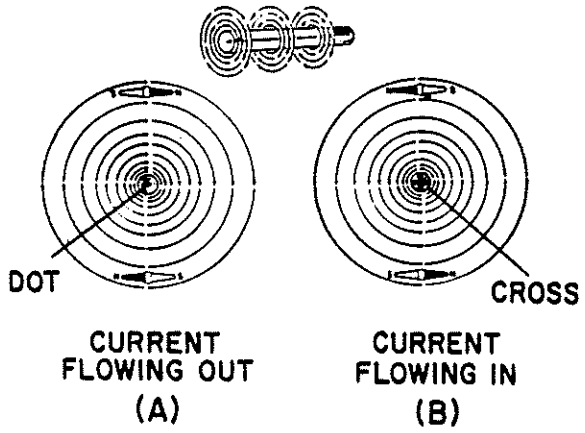


Figure 7-2.—Magnetic field around a current-carrying conductor, detailed view.

POLARITY OF AN ELECTROMAGNETIC COIL

In figure 7-2, it was shown that the direction of the magnetic field around a straight conductor depends on the direction of current flow through that conductor. Thus, a reversal of current flow through a conductor causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current flow through a coil also causes a reversal of its two-pole field. This is true because that field is the product of the linkage between the individual turns of wire on the coil. Therefore, if the field of each turn is reversed, it follows that the total field (coil's field) is also reversed.

When the direction of electron flow through a coil is known, its polarity may be determined by use of the LEFT-HAND RULE FOR COILS. This rule is illustrated in figure 7-5, and is stated as follows: GRASPING THE COIL IN THE LEFT HAND, WITH THE FINGERS "WRAPPED AROUND" IN THE DIRECTION OF ELECTRON

FLOW, THE THUMB WILL POINT TOWARD THE NORTH POLE.

STRENGTH OF AN ELECTROMAGNETIC FIELD

The strength, or intensity, of a coil's field depends on a number of factors. The major factors are listed below. All of these factors are discussed under headings that follow.

1. The number of turns of conductor.
2. The amount of current flow through the coil.
3. The ratio of the coil's length to its width.
4. The type of material in the core.

Magnetic Circuits

Many electrical devices depend upon magnetism in one or more forms for their operation. To have these devices function efficiently, engineers work out intricate designs for the required magnetic conditions. The magnets designed to do a particular job must have the required strength, and must be provided with paths, or circuits, of suitable shapes and materials.

A magnetic circuit is defined as the path (or paths) taken by the magnetic lines of force leaving a north pole, passing through the entire circuit and returning to the south pole. A magnetic circuit may be a series or parallel circuit or any combination.

Ohm's Law Equivalent for Magnetic Circuits

The law of current flow in the electric circuit is similar to the law for the establishing of flux in the magnetic circuit.

Ohm's law for ELECTRIC circuits states that the current is directly proportional to the applied voltage and inversely proportional to the resistance offered by the circuit. Expressed mathematically,

$$I = \frac{E}{R}.$$

Rowland's law for MAGNETIC circuits states, in effect, that the number of lines of magnetic flux in maxwells (Φ) is directly proportional to the magnetomotive force in gilberts (F) and inversely proportional to the reluctance ($\mathcal{R}$) offered by the circuit. The unit of reluctance sometimes used is the REL, $\mathcal{R}$. Expressed mathematically,

$$\Phi = \frac{F}{\mathcal{R}}.$$

The similarity of Ohm's law and Rowland's law is apparent. However, the units used in the expression for Rowland's law need to be explained.

The MAGNETIC FLUX, Φ, (phi) is similar to current in the Ohm's law formula, and comprises the total number of lines of force existing in the magnetic circuit. The MAXWELL is the unit of flux—that is, 1 line of force is equal to 1 maxwell. However, the maxwell is often referred to as simply a LINE OF FORCE, LINE OF INDUCTION or LINE.

The MAGNETOMOTIVE FORCE, F, or m. m. f., comparable to electromotive force in the Ohm's law formula, is the force that produces the flux in the magnetic circuit. The practical unit of magnetomotive force is the AMPERE-TURN. Another unit of magnetomotive force sometimes used is the GILBERT, designated by the capital letter, F. The gilbert is the magnetomotive force required to establish 1 maxwell in a magnetic circuit having 1 unit of reluctance (1 rel). The magnetomotive force in gilberts is expressed in terms of ampere-turns as

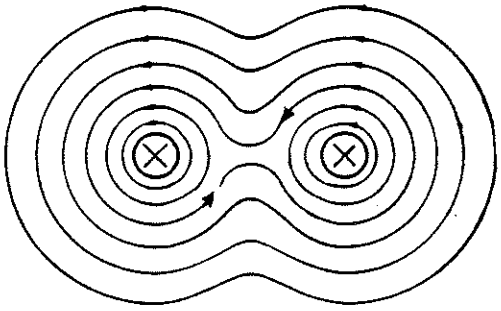
$$F = 1.257IN,$$

where F is in gilberts, I is in amperes, and N is the number of complete turns of wire encircling the circuit.

The UNIT OF INTENSITY of magnetizing force per unit of length is designated as H, and is sometimes expressed as gilberts per centimeter of length. Expressed mathematically,

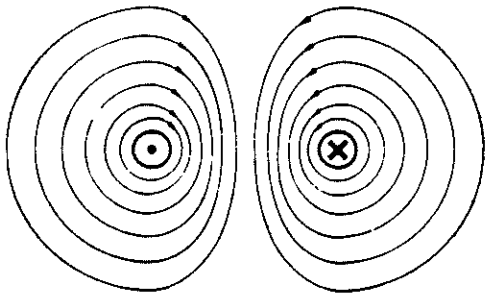
$$H = \frac{1.257IN}{l},$$

where l is the length in centimeters.



CURRENTS FLOWING IN THE SAME DIRECTION

(A)



CURRENTS FLOWING IN OPPOSITE DIRECTIONS

(B)

Figure 7-3.—Magnetic field around two parallel conductors.

The RELUCTANCE, $\mathcal{R}$, similar to resistance in the Ohm's law formula, is the opposition offered by the magnetic circuit to the passage of magnetic flux. The unit of reluctance has not been named officially. However, the REL has been proposed, and the symbol $\mathcal{R}$ is commonly used. The unit of reluctance is the reluctance of 1 centimeter-cube of air. The reluctance of a magnetic substance varies directly as the length of the flux path and inversely as the cross-sectional area and the permeability, μ, of the substance. Expressed mathematically,

$$\mathcal{R} = \frac{l}{\mu A},$$

where l is the length in centimeters, and A is the cross-sectional area in square centimeters.

PERMEABILITY, designated by the Greek letter mu, μ, is treated under a separate heading.

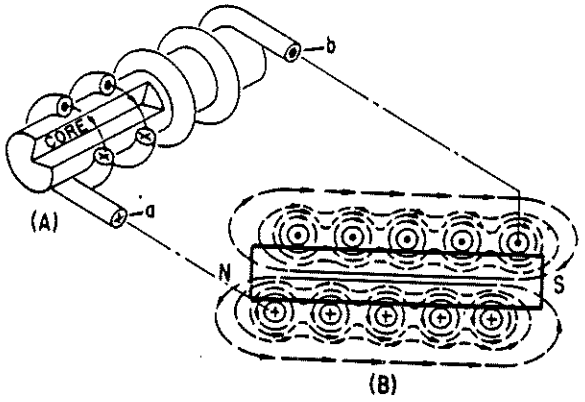


Figure 7-4.—Magnetic field produced by a current-carrying coil.

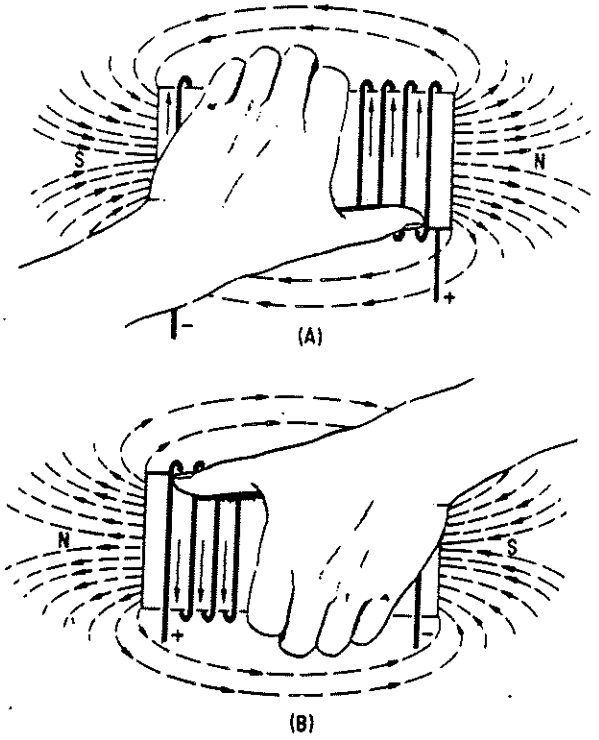


Figure 7-5.—Left-hand rule for coil polarity.

However, it is defined here to permit a fuller interpretation of Rowland's law and also a practical application of this law. Permeability is a measure of the relative ability of a substance to conduct magnetic lines of force as compared with air. The permeability of air is taken as 1. Permeability is indicated as the ratio of the flux density in lines per square centimeter (gauss,

B) to the intensity of the magnetizing force in gilberts per centimeter of length, indicated by *H*. Expressed mathematically,

$$\mu = \frac{B}{H}.$$

Another term used in magnetic circuits is PERMEANCE. Permeance, indicated by the symbol, *P*, is the reciprocal of reluctance—that is,

$$P = \frac{1}{\mathcal{R}}$$

Values of *B*, *H*, and μ for common magnetic substances are given in table 7-1.

Permeance is like conductance in electric circuits, and is defined as the property of a magnetic circuit that permits lines of magnetic flux to pass through the circuit.

Table 7-1.–B, H, and μ for common magnetic material.*

B	Sheet steel		Cast steel		Wrought iron		Cast iron	
	H	μ	H	μ	H	μ	H	μ
3,000	1.3	2,310	2.8	1,070	2.0	1,500	5.0	600
4,000	1.6	2,500	3.4	1,177	2.5	1,600	8.5	471
5,000	1.9	2,630	3.9	1,281	3.0	1,666	14.5	347
6,000	2.3	2,605	4.5	1,332	3.5	1,716	24.0	250
7,000	2.6	2,700	5.1	1,371	4.0	1,750	38.5	182
8,000	3.0	2,666	5.8	1,380	4.5	1,778	60.0	133
9,000	3.5	2,570	6.5	1,382	5.0	1,800	89.0	101
10,000	3.9	2,560	7.5	1,332	5.6	1,782	124.0	80.6
11,000	4.4	2,500	9.0	1,222	6.5	1,692	166.0	66.4
12,000	5.0	2,400	11.5	1,042	7.9	1,520	222.0	54.1
13,000	6.0	2,166	16.0	813	10.0	1,300	290.0	44.8
14,000	9.0	1,558	21.5	651	15.0	934	369.0	38.0
15,000	15.5	970	32.0	469	25.0	600	....	...
16,000	27.0	594	49.0	327	49.0	327	....	...
17,000	52.5	324	74.0	230	93.0	183	....	...
18,000	92.0	196	115.0	156	152.0	118	....	...
19,000	149.0	127	175.0	108	229.0	83	....	...
20,000	232.0	86	285.0	70	....	....	....	...

*B = flux density in lines per square centimeter; H = gilberts per centimeter of length; μ = permeability; $\mu = \frac{B}{H}$.

A comparison of the units, symbols, and equations used in applying Ohm's law to electric circuits and Rowland's law to magnetic circuits is given in table 7-2.

Table 7-2.–Comparison of electric and magnetic circuits.

	Electric circuit	Magnetic circuit
Force.	Volt, E, or e.m.f.	Gilberts, F, or m.m.f.
Flow	Ampere, I	Flux, Φ, in maxwells
Opposition.	Ohms, R	Reluctance, $\mathcal{R}$, or rels
Law.	Ohm's law, $I = \frac{E}{R}$	Rowland's law, $\Phi = \frac{F}{\mathcal{R}}$
Intensity of force .	Volts per cm. of length	$H = \frac{1.257IN}{\ell}$, gilberts per centimeter of length.
Density.	Current density—for example, amperes per $cm.^2$.	Flux density—for example, lines per $cm.^2$, or gausses.

As a practical application of Rowland's law, let it be required to find the ampere-turns *(IN)* necessary to produce 20,000 lines of flux in a CAST STEEL ring having a cross-sectional area of 4 square centimeters and an average length of 20 centimeters, as shown in figure 7-6.

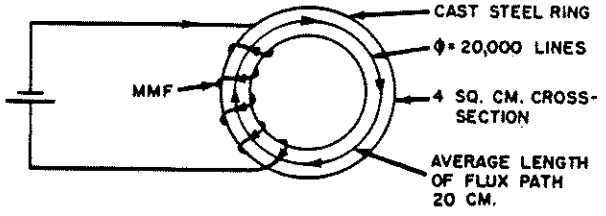


Figure 7-6.—Determining ampere-turns in a magnetic circuit.

Flux density B is expressed as

$$B = \frac{\Phi}{A} = \frac{200,000}{4} = 5,000 \text{ lines/cm.}^2,$$

and from table 7-1 the corresponding value of H for cast steel is 3.9. The formula for H has previously been given as

$$H = \frac{1.257IN}{l},$$

from which

$$IN = \frac{Hl}{1.257}.$$

Substituting 3.9 for H and 20 for l in the preceding equation,

$$IN = \frac{3.9 \times 20}{1.257} = 62 \text{ ampere-turns.}$$

Properties of Magnetic Materials

PERMEABILITY

When an annealed sheet steel core is used in an electromagnet it produces a stronger magnet than if a cast iron core is used. This is true because annealed sheet steel is more readily acted upon by the magnetizing force of the coil than is hard cast iron. In other words, soft sheet steel is said to have greater permeability because the magnetic lines are established more easily in it than in cast iron. The ratio of the flux produced by a coil when the core is iron (or some other substance) to the flux produced when the core is air is called the PERMEABILITY of the iron (or whatever substance is used), the current in the coil being the same in each case. The permeability of a substance is thus a measure of the relative ability to conduct magnetic lines of force, or its magnetic conductivity. The permeability of air is 1. The permeability of nonmagnetic materials, such as wood, aluminum, copper, and brass is essentially unity, or the same as for air.

Magnetization curves for the four magnetic materials listed in table 7-1 are given in figure 7-7.

The permeability of magnetic materials varies with the degree of magnetization, being smaller for high values of flux density, as is indicated in table 7-1 and figure 7-8.

HYSTERESIS

The simplest method of illustrating the property of hysteresis is by graphical means such as the hysteresis loop shown in figure 7-9.

In this figure the magnetizing force is indicated in gilberts per centimeter of length along the plus and minus H axis, and the flux density is indicated in gausses along the plus and minus B axis. The intensity of the magnetizing force, H, applied by means of a current-carrying coil of wire around the sample of magnetic material, is varied uniformly through one cycle of operation, starting at zero. The force, H, is increased in the positive direction (current flowing in a given direction through the coil) to 11 gilberts per centimeter. During this time the flux density, B, increases from zero to 14,000 at point A. If H is decreased to zero, the descending curve of flux density does not return to zero via its rise path. Instead, it returns to point B, where the flux density is 13,000. The magnetic flux indicated by the length of line OB represents the RETENTIVITY of the magnetic substance.

Retentivity is the ability of a magnetic substance to retain its magnetism after the magnetizing force has been removed. Retentivity is most apparent in hard steel and is least apparent in soft iron.

The value of the RESIDUAL, or remaining, MAGNETISM when H has been reduced to zero, depends on the substance used and the degree

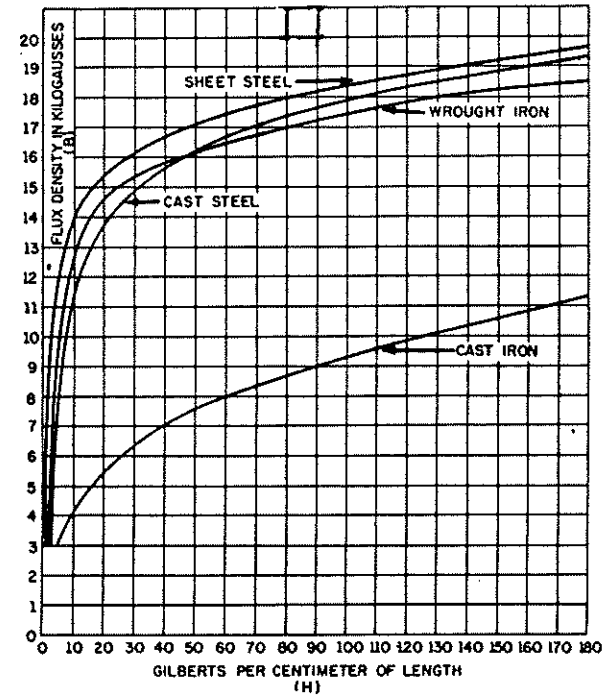


Figure 7-7.—Magnetization curves for four magnetic materials.

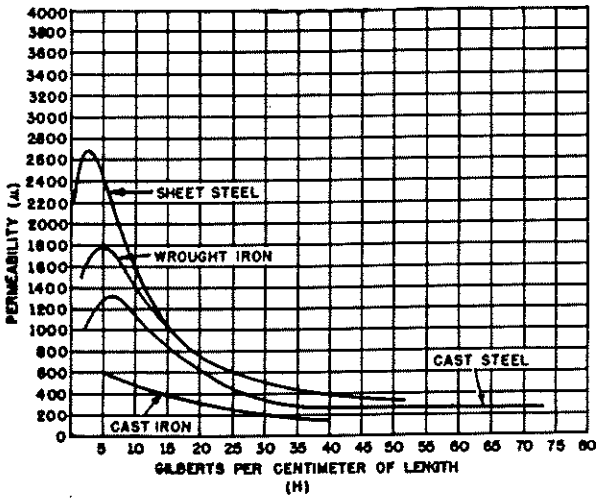


Figure 7-8.—Permeability curves.

of flux density attained. In this example the residual magnetism is 13,000 gausses.

If current is now sent through the coil in the opposite direction, so that the intensity of the magnetizing force becomes $-H$, the force will have to be increased to point C before the residual magnetism is reduced to zero. The magnetizing force, OC, necessary to reduce

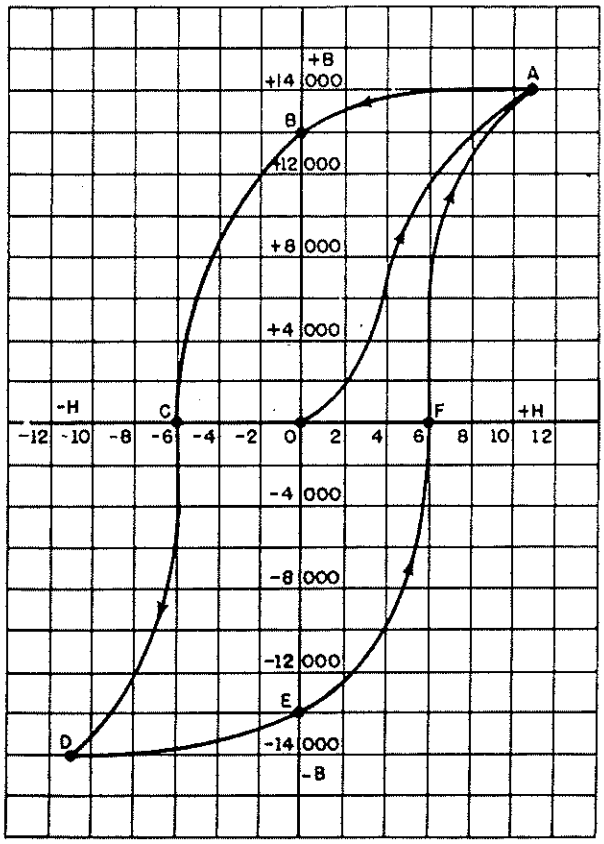


Figure 7-9.—Hysteresis loop.

the residual magnetism to zero is called the COERCIVE FORCE. In this example the coercive force is 6 gilberts per centimeter.

If the magnetizing force is continued to -11 gilberts per centimeter, the curve descends from C to D, magnetizing the sample of magnetic material with the opposite polarity. If the magnetizing force is reduced again to zero, the flux density is reduced to point E. The magnetic flux indicated by the length of line OE represents the retentivity of the magnetic substance, as did line OB. The residual magnetism is again 13,000 gausses.

If the current through the coil is again reversed (sent through in the original direction), the magnetization curve moves to zero when the magnetizing force is increased to point F.

Thus, when the magnetizing force goes through a complete cycle, the resulting magnetization likewise goes through a complete cycle.

From the foregoing analysis it is apparent that hysteresis is the property of a magnetic

substance that causes the magnetization to lag behind the force that produces it. The lag of magnetization behind the force that produces it is caused by molecular friction. Energy is needed to move the molecules (or domains) through a cycle of magnetization. If the magnetization is reversed slowly, the energy loss may be negligible. However, if the magnetization is reversed rapidly, as when commercial alternating current is used, considerable energy may be dissipated. If the molecular friction is great, as when hard steel is used, the losses may be very great. Another factor that determines hysteresis loss is the maximum density of the flux established in the magnetic material.

A comparison of the hysteresis loops for annealed steel and hard steel is shown in figure 7-10. The area within each loop is a measure of the hysteresis energy loss per cycle of operation. Thus, as shown in the figure, more energy is dissipated in molecular friction in hard steel than in annealed steel. It is therefore important that substances having low hysteresis loss be used for transformer cores and similar a-c applications.

Electromagnets

An electromagnet is composed of a coil of wire wound around a core of soft iron. When direct current flows through the coil the core will become magnetized with the same polarity that the coil (solenoid) would have without the core. If the current is reversed, the polarity of both the coil and the soft-iron core is reversed.

The polarity of the electromagnet is determined by the left-hand rule in the same manner that the polarity of the solenoid in figure 7-5 was determined. If the coil is grasped in the left hand in such a way that the fingers curve around the coil in the direction of electron flow (- to +), the thumb will point in the direction of the north pole.

The addition of the soft-iron core does two things for the current-carrying coil, or solenoid. First, the magnetic flux is increased because the soft-iron core is more permeable than the air core; second, the flux is more highly concentrated. The permeability of soft iron is many times that of air, and therefore the flux density is increased considerably when a soft-iron core is inserted in the coil.

The magnetic field around the turns of wire making up the coil influences the molecules in the iron bar causing, in effect, the individual molecular magnets, or domains, to line up in the direction of the field established by the coil. Essentially the same effect is produced in a soft-iron bar when it is under the influence of a permanent magnet.

The magnetomotive force resulting from the current flow around the coil does not increase the magnetism that is inherent in the iron core, it merely reorientates the "atomic" magnets that were present before the magnetizing force was applied. If substantial numbers of the tiny magnets are orientated in the same direction, the core is said to be magnetized.

When soft iron is used, most of the atomic magnets return to what amounts to a miscellaneous orientation upon removal of the magnetizing current, and the iron is said to be demagnetized. If hard steel is used, more of them will remain in alinement with the direction of the flux produced by the flow of current through the coil, and the metal is said to be a permanent magnet. Soft iron and other magnetic materials having high permeability and low retentivity are generally used in electromagnets.

It is known from experience that a piece of soft iron is attracted to either pole of a permanent magnet. A soft-iron bar is likewise attracted by a current-carrying coil, if the coil and bar are orientated as in figure 7-11. As shown in the figure, the lines of force extend through the soft iron and magnetize it. Because unlike poles attract, the iron bar is pulled toward the coil. If the bar is free to move, it will be drawn into the coil to a position near the center where the field is the strongest.

The SOLENOID-AND-PLUNGER TYPE of magnet in various forms is employed extensively aboard ships and aircraft. These are used to operate the feeding mechanism of carbon-arc searchlights; to open circuit-breakers automatically when the load current becomes excessive; to close switches for motorboat starting; to fire guns; and to operate flood valves, magnetic brakes, and many other devices.

The ARMATURE-TYPE of electromagnet also has extensive applications. In this type of magnet the coil is wound on and insulated from the iron core. The core is not movable. When

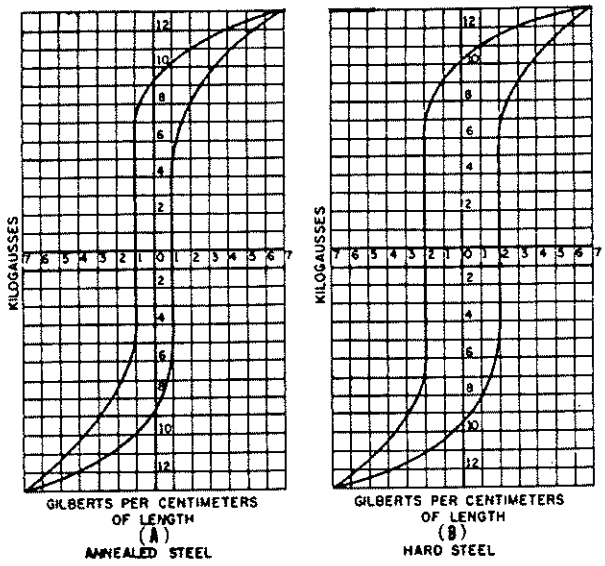


Figure 7-10.–Comparison of hysteresis loops.

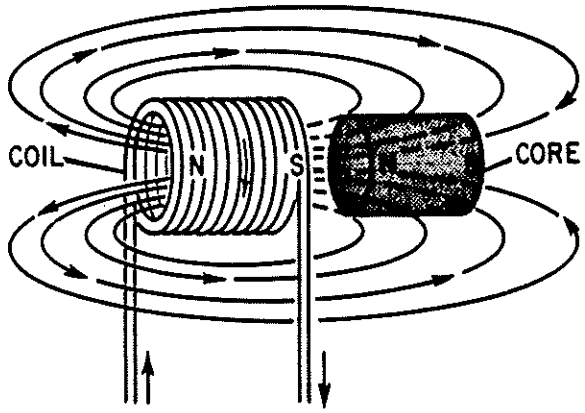


Figure 7-11.–Solenoid with iron core.

current flows through the coil the iron core becomes magnetized and causes a pivoted soft-iron armature located near the electromagnet, to be attracted toward it. This type of magnet is used in door bells, relays, circuit breakers, telephone receivers, and so forth.

APPLICATIONS OF ELECTROMAGNETS

Electric Bell

The electric bell is one of the most common devices employing the electromagnet. A simple electric bell is shown in figure 7-12. Its operation is explained as follows:

1. When the switch is closed, current flows from the negative terminal of the battery, through the contact points, the spring, the two coils, and back to the positive terminal of the battery.
2. The cores are magnetized, and the soft-iron armature (magnetized by induction) is pulled down, thus causing the hammer to strike the bell.
3. At the instant the armature is pulled down, the contact is broken, and the electromagnet loses its magnetism. The spring pulls the armature up so that contact is reestablished, and the operation is repeated. The speed with which the hammer is moved up and down depends on the stiffness of the spring and the mass of the moving element.

The magnetomotive forces of the two coils are in series aiding and therefore the magnetization of the core is increased over that produced by one coil alone.

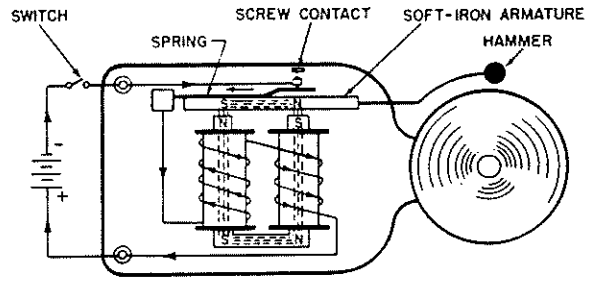


Figure 7-12.–Electric bell.

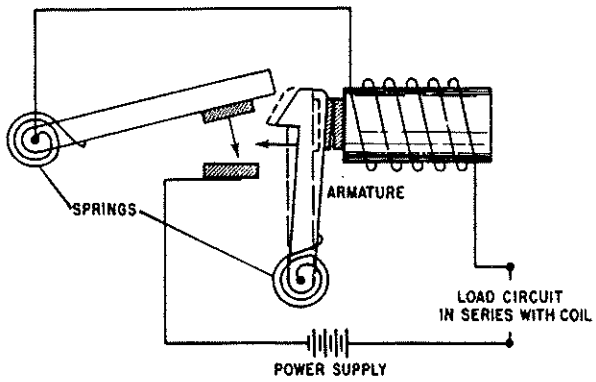


Figure 7-13.–Magnetic circuit breaker.

Circuit Breaker

A circuit breaker, like a fuse, protects a circuit against short circuits and overloading. In this device the winding of an electromagnet is

connected in series with the load circuit to be protected and with the switch contact points. The principle of operation is shown in figure 7-13. Excessive current through the magnet winding causes the switch to be tripped, and the circuit to both breaker and load is opened by a spring. When the circuit fault has been cleared, the circuit is closed again by manually resetting the circuit breaker.

Many more applications of electromagnets are discussed throughout this course. Their applications to generators, motors, voltage regulators, reverse current relays, and servomechanisms will be covered.

QUIZ

1. Reversing the current flow through a coil
   a. reduces the amount of flux produced
   b. reverses its two-pole field
   c. reduces power consumed
   d. reduces eddy currents
2. The unit of magnetic flux is
   a. ampere-turn
   b. gilbert
   c. intensity
   d. maxwell
3. Flux in a magnetic circuit compares in an electrical circuit with
   a. voltage
   b. current
   c. resistance
   d. opposition
4. If a compass is placed in the vicinity of a conductor carrying d.c., the needle alines itself
   a. in the direction of current flow in the conductor
   b. at the right angles to the conductor
   c. in the general direction of the north pole
   d. in the general direction of the south pole
5. The left-hand rule for coils states: Grasping the
   a. coil with the left hand, with fingers pointing in the direction of the magnetic field, the middle finger will point to the north pole
   b. coil with the left hand, thumb pointing in the direction of the conductor movement, the fingers will point in the direction of the magnetic field
   c. conductor with the left hand, fingers pointing in the direction of the north pole, the thumb will indicate current flow
   d. coil in the left hand, fingers wrapped around in the direction of electron flow, the thumb will point towards north pole
6. The word permeability indicates the
   a. amount of reluctance of one centimeter-cube of air
   b. number of turns of an air core
   c. ability of a substance to conduct magnetic lines of force
   d. m.m.f. required to produce one gilbert
7. If an iron core is inserted part way into a coil and current is applied to the coil, the core will be drawn into the coil in an effort to
   a. increase reluctance of the magnetic circuit
   b. decrease the length of the magnetic circuit
   c. reduce the permeability of the circuit
   d. increase the residual effect
8. Current flow in a straight conductor produces
   a. hysteresis
   b. magnetic lines of force
   c. a north pole
   d. permeability
9. The inductance of a coil depends upon the
   a. number of turns, current flow, type of core material, and ratio of coil's length to its width
   b. current, flux, and core material
   c. direction of rotation, flux, and speed
   d. permeability, reluctance, gausses, and maxwells
10. The ability of a magnetic substance to hold its magnetism after the magnetizing force has been removed is
    a. residual
    b. retentivity
    c. hysteresis
    d. permeability
11. The solenoid and plunger type of magnet is employed in various forms to control
    a. electrical equipment
    b. hysteresis losses
    c. permeability
    d. all of the above
12. When using the left-hand rule for a conductor
    a. grasp the conductor with fingers pointing in the direction of current flow and thumb will indicate direction of field
    b. the compass will point in the direction of current flow and fingers will indicate direction of magnetic field
    c. grasp the conductor with the thumb extended in the direction of electron flow, the fingers will point in the direction of the magnetic lines of force
    d. reverse the current flow and thumb will point in direction of the magnetic field

13. The magnetic circuit is determined by
    a. lines of force leaving the south pole and entering the north pole externally
    b. permeability to current and the north pole
    c. maxwells to length in centimeters and the south pole
    d. the complete path taken by magnetic lines leaving the north pole, and returning to the north pole
14. In what material is retentivity most apparent?
    a. Hard steel
    b. Soft iron
    c. Copper
    d. Wood
15. The armature type of electromagnet
    a. has a movable iron bar in its magnetic circuit
    b. uses a permanent magnet core
    c. has a hard steel core and a pivoted bar of copper
    d. has a movable iron core
16. When two parallel conductors carrying current in the same direction are placed side by side, the fields produced by both
    a. cancel each other's field
    b. push each other apart
    c. form a north pole
    d. encircle each other, drawing the conductors together
17. The equivalent Ohm's law formula for magnetic circuits is
    a. $I = \frac{e}{r}$
    b. $R = \frac{I}{E}$
    c. $\Phi = \frac{E}{R}$
    d. $P = \frac{I}{E}$
18. Which of the following materials incurs low hysteresis loss when used for transformer cores and similar applications?
    a. Hard steel
    b. Annealed steel
    c. Soft iron
    d. Cast steel
19. The magnetic field around a current-carrying wire
    a. is parallel to the current flow in the conductor
    b. exists at all points along its length
    c. exists only at the beginning of electron movement
    d. moves in the direction of current flow
20. Direct current flows through a coil of wire which has an iron core. When the iron core is removed and all other factors remain unchanged, the total number of lines of force through the coil will change because
    a. changing the core material affects m.m.f.
    b. permeance has been increased
    c. reluctance has been increased
    d. the permeability of the magnetic circuit has been increased
21. When loops of wire are formed into a coil and current is passed through this coil
    a. the result is a permanent magnet
    b. each turn will cancel the magnetic field of each adjacent turn
    c. the magnetic field of each turn of wire links with the fields of adjacent turns
    d. permeability decreases to minimum

CHAPTER 8

INTRODUCTION TO ALTERNATING-CURRENT ELECTRICITY

In the study of batteries you learned that electrons flow continually in one direction—from the negative terminal to the positive terminal, via the load.

In the case of alternating current, electrons are made to move first in one direction and then in the other. The direction of current flow reverses periodically.

Basic A-C Generator

An alternating-current generator converts mechanical energy into electrical energy. It does this by utilizing the principle of electromagnetic induction. In the study of magnetism, it was shown that a current-carrying conductor produces a magnetic field around itself. It is also true that a changing magnetic field may produce an e.m.f. in a conductor. If a conductor lies in a magnetic field, and either the field or conductor moves, an e.m.f. is induced in the conductor. This effect is called electromagnetic induction.

CYCLE

Figure 8-1 shows a suspended loop of wire (conductor) being rotated (moved) in a counterclockwise direction through the magnetic field between the poles of a permanent magnet. For ease of explanation, the loop has been divided into a dark and a light half. Notice that in part (A), the dark half is moving along (parallel to) the lines of force. Consequently, it is cutting none of these lines. The same is true of the light half, moving in the opposite direction. Since the conductors are cutting no lines of force, no e.m.f. is induced. As the loop rotates toward the position shown in part (B), it cuts more and more lines of force per second because it is cutting more directly across the field (lines of force) as it approaches the position shown in (B). At position (B) the induced voltage is greatest because the conductor is cutting directly across the field.

As the loop continues to be rotated toward the position shown in part (C), it cuts fewer and fewer lines of force per second. The induced voltage decreases from its peak value. Eventually, the loop is once again moving in a plane parallel to the magnetic field, and no voltage (zero voltage) is induced. The loop has now been rotated through half a circle (one alternation, or 180°). The sine curve shown in the lower part of the figure shows the induced voltage at every instant of rotation of the loop. Notice that this curve contains 360°, or two alternations. Two alternations represent one complete cycle of rotation.

The direction of current flow during the rotation from (B) to (C), when a closed path is provided across the ends of the conductor loop, can be determined by using the LEFT-HAND RULE FOR GENERATORS. The left-hand rule is applied as follows: Extend the left hand so that the THUMB points in the direction of conductor movement, and the FOREFINGER points in the direction of magnetic flux (north to south). By pointing the MIDDLE FINGER 90 degrees from the forefinger, it will point in the direction of current flow within the conductor.

Applying the left-hand rule to the dark half of the loop in part (B), you will find that the direction of current flow is as shown by the heavy arrow. Similarly, you can determine the direction of current flow through the light half of the loop. The two induced voltages add together to form one total e.m.f. When the loop is further rotated to the position shown in part (D), the action is reversed. The dark half is moving

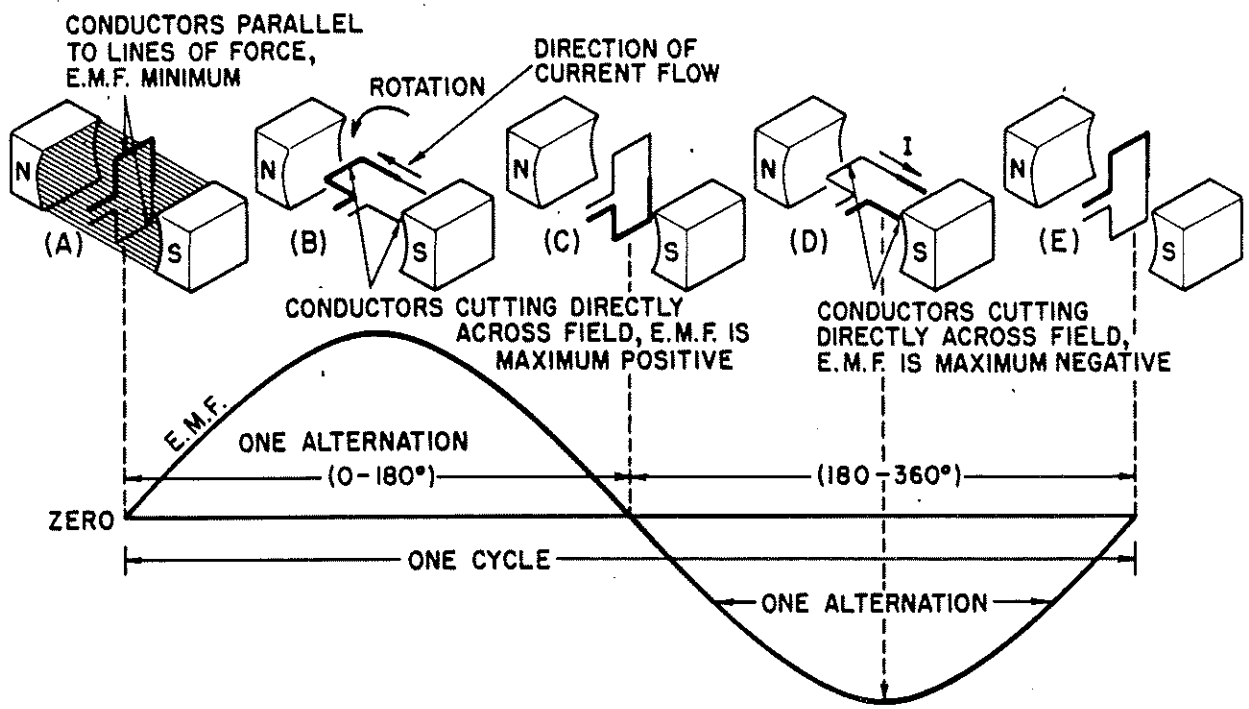


Figure 8-1.—Basic alternating-current generator.

up instead of down, and the light half is moving down instead of up. By applying the left-hand rule once again, you will find that the direction of the induced e.m.f. and its resulting current have reversed. The voltage builds up to maximum in this new direction, as shown by the sine-wave tracing. The loop finally returns to its original position (part E), at which point voltage is again zero. The wave of induced voltage has gone through one complete cycle.

If the loop is rotated at a steady rate, and if the strength of the magnetic field is uniform, the number of cycles per second and the voltage will remain at fixed values. Continuous rotation will produce a series of sine-wave voltage cycles, or, in other words, an a-c voltage. In this way mechanical energy is converted into electrical energy.

The rotating loop in figure 8-1 is called an armature. The armature may have any number of loops or coils.

FREQUENCY

The frequency of an alternating current or voltage is the number of complete cycles occurring in each second of time. Hence, the speed of rotation of the loop determines the frequency. For a single loop rotating in a two-pole field you can see that each time the loop makes one complete revolution the current reverses direction twice. A single cycle of a-c per second will result if the loop makes one revolution each second. If it makes two revolutions per second, the output frequency will be two cycles per second. In other words, the frequency of a two-pole generator happens to be the same as the number of revolutions per second. As the speed is increased, the frequency is increased.

If an alternating-current generator has four pole pieces, as in figure 8-2, every complete mechanical revolution of the armature will produce TWO a-c cycles. When the dark half of the loop passes between poles *S*1 and *N*2, a voltage is induced which causes current to flow into the dark slipring attached to the end of the loop.

When the dark half passes between *N*2 and *S*2, the induced voltage reverses direction. Another reversal occurs when it passes between *S*2 and *N*1. The voltage at the sliprings reverses direction FOUR TIMES during each revolution. In other words, two cycles of a-c voltage are generated for each mechanical revolution. If each revolution lasts one second, the frequency of the output is two cycles per second. The more

poles that are added, the higher the frequency per revolution becomes. To find the output frequency of any a-c generator, the following formula can be used:

$$f = \frac{P \times \text{r.p.m.}}{120}$$

where f is frequency in cycles per second, r.p.m. is revolutions per minute, and P is the number of poles.

A generator made to deliver 60 cycles per second (c.p.s.), having two field poles, would need an armature designed to rotate at 3,600 r.p.m. If it had four field poles, it would need an armature designed to rotate at 1,800 r.p.m. In either case, frequency would be the same. In actual practice, a generator designed for low-speed operation generally has a greater number of pole pieces, while a high-speed machine will have relatively fewer pole pieces, if both are to deliver power at the same frequency.

PERIOD

The period of an a-c voltage or current of sine waveform is the time for one complete cycle, or $1/f$. For example, the period of a 60-cycle voltage is 1/60 of a second; that of a 50-cycle voltage is 1/50 second.

GENERATED VOLTAGE

Alternating-current generators are usually constant-potential machines because they are driven at constant speed and have fixed magnetic field strength for a given load. The effective voltage, E, generated by a single-winding (phase) a-c generator is related to the total field strength per pole, Φ; the frequency, f; and the total number of active conductors, N, in the armature winding; as indicated in the following equation:

$$E = 2.22\,\Phi f N 10^{-8}$$

For example, if $\Phi = 2.5 \times 10^6$, $f = 60$ cycles per second, and $N = 96$ conductors, the voltage generated is

$$E = 2.22 \times 2.5 \times 10^6 \times 60 \times 96 \times 10^{-8}$$

$$E = 320 \text{ volts.}$$

(The factors of poles (P) and speed (S in r.p.m.), which appear in the equation for generated voltage in multipolar series-wound d-c generators, do not appear in the formula for the voltage generated in each phase of the a-c generator. This is because they are replaced by the equivalent factor of frequency ($f = \frac{PS}{120}$).

The length of active conductor extending under a pole does not appear in the equation directly because it is included in the factor of total magnetic flux per pole. The longer the active conductor, the more flux there will be for each pole, since the pole length and conductor length are assumed to be the same. For example, if an active conductor length is doubled, the pole length is doubled, the flux per pole is doubled, and the generated voltage is doubled.

Analysis of Sine Wave of Voltage

VECTORS DEFINED

As mentioned previously, an alternating current or voltage is one in which the direction changes periodically. The electron movement is first in one direction, then in the other. The variation is of sine waveform. Straight lines drawn to scale, called VECTORS, are used in solving problems involving sine-wave currents and voltages.

A simple vector is a straight line used to denote the magnitude and direction of a given quantity. Magnitude is denoted by the length of the line, drawn to scale, and direction is indicated by an arrow at one end of the line, together with the angle that the vector makes with a horizontal reference vector.

For example, if a certain point B (fig. 8-3) lies 1 mile east of point A, the direction and distance from A to B can be shown as vector e by using a scale of approximately 1/2 inch = 1 mile.

Vectors may be rotated like the spokes of a wheel to generate angles. Positive rotation is counterclockwise and generates positive angles. Negative rotation is clockwise and generates negative angles.

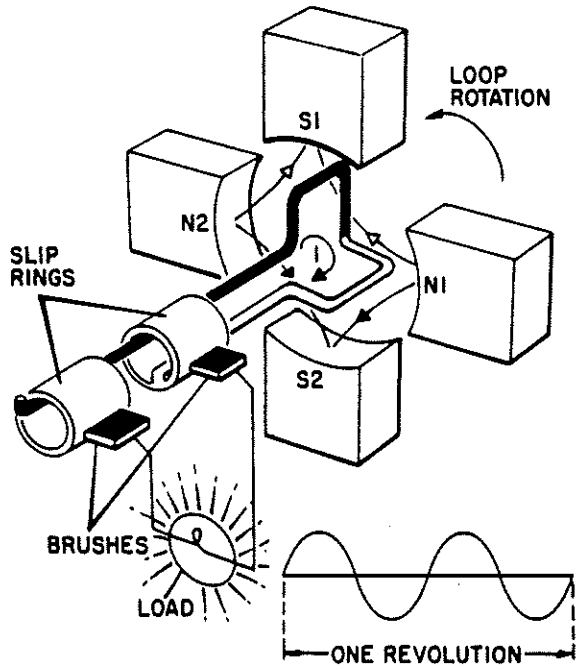


Figure 8-2.—Four-pole basic a-c generator.

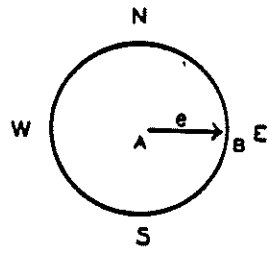


Figure 8-3.—Designating direction and distance by vectors.

The vertical projection (dotted line in fig. 8-4) of a ROTATING VECTOR may be used to represent the voltage at any instant. Vector E_m represents the maximum voltage induced in a conductor rotating at uniform speed in a 2-pole field (points 3 and 9). The vector is rotated counterclockwise through one complete revolution (360°). The point of the vector describes a circle. A line drawn from the point of the vector perpendicular to the horizontal diameter of the circle is the vertical projection of the vector.

The circle also describes the path of the conductor rotating in the bi-polar field. The vertical projection of the vector represents the voltage generated in the conductor at any instant corresponding to the position of the rotating vector as indicated by angle θ. Angle θ represents selected instants at which the generated voltage is plotted. The sine curve plotted at the right of the figure represents successive values of the a-c voltage induced in the conductor as it moves at uniform speed through the 2-pole field because the instantaneous values of rotationally induced voltage are proportional to the sine of the angle θ that the rotating vector makes with the horizontal.

EQUATION OF SINE WAVE OF VOLTAGE

The sine curve is a graph of the equation

$$e = E_m \sin \theta,$$

where e is the instantaneous voltage, E_m is the maximum voltage, θ is the angle of the generator armature, and "sine" is one of the trigonometric functions shown in figure 8-4.

The instantaneous voltage, e, depends on the sine of the angle. It rises to a maximum positive value as the angle reaches 90°. This occurs because the conductor cuts directly across the flux at 90°. It falls to zero at 180°, because the conductor cuts no lines of flux at 180°. It reaches a negative peak at 270°, and becomes zero again at 360°. For example, when θ = 60° and E_m = 100 volts, e = 100 x sin 60° = 86.6 volts. When θ = 240°, e = 100 sin 240° = -86.6 volts.

Another form of the trigonometric equation for a sine wave of voltage involves the angular velocity of its rotating vector. The term "angular velocity" refers to the number of degrees (angles) through which a voltage vector rotates per second. Angular velocity is symbolized by the Greek letter omega (ω). In practice, ω is generally given in terms of RADIANS per second, rather than degrees per second. A radian is a segment of the circumference of a circle. This segment is always exactly equal in length to the RADIUS of that circle. There are π (3.14) radians in half a circle, and 2π (6.28) radians in the circumference of a complete circle. Therefore, when a voltage vector makes one complete revolution, describing one complete circle, it traverses 2π or 6.28 radians. In terms of degrees of rotation, one radian is 360°/6.28 or 57.32°.

The number of radians per second traversed by an alternating-voltage vector is

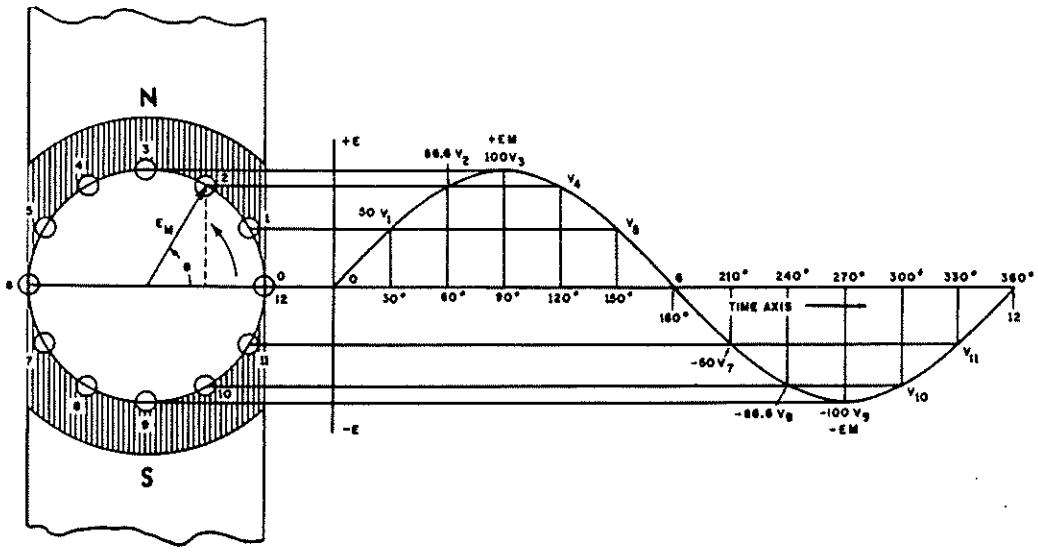


Figure 8-4.—Generation of sine-wave voltage.

closely related to its frequency, because either may be used to express the other. Since one vector revolution equals one complete cycle, then each cycle equals 6.28 radians of vector travel. That is, an alternating voltage whose frequency is 60 cycles would be said to have an angular velocity of 6.28 x 60, or roughly 377 radians per second. Written as a formula, angular velocity is $\omega = 2\pi f$. Thus, in a formula involving angular velocity, the term $2\pi f$ may be replaced by the simpler symbol ω, if convenient. As previously stated, another form of the trigonometric equation for a sine wave of voltage involves the angular velocity of the generating vector.

The equation is

$$e = E_m \times \sin \omega t.$$

It is used to determine the voltage of a rotating vector at some given instant of time. The starting reference, or "time zero," is usually when the voltage vector is at a peak positive value. The equation time factor t is the elapsed time from time zero, and is the exact instant at which the voltage is to be determined. To determine the exact angular position at any instant, multiply the angular velocity (ω) of the vector by the time elapsed (t). By dividing elapsed time t by the period for one cycle, and multiplying by 360°, the angular position of the voltage vector may be determined for any instant. Multiplying E_m by the sine of that instantaneous angle will yield the instantaneous voltage e.

For example, consider a 60-cycle voltage whose peak value is 100 volts. Assume you must determine the voltage 0.00139 second after the voltage has reached a positive peak.

$$\sin t = \sin 2\pi ft = \sin 360(60)(0.00139) = \sin 30° = 0.5$$

The instantaneous voltage e is

$$e = E_m \times \sin 30°$$

$$e = 100 \times 0.5$$

$$e = 50 \text{ volts.}$$

There are four important values associated with sine waves of voltage or current:

Instantaneous—designated as e or i; maximum—designated as E_m or I_m; average—designated as E_{avg} or I_{avg}; and effective—designated as E or I.

The INSTANTANEOUS value may be any value between zero and maximum depending on the instant chosen, as indicated by the equation $e = E_m \sin \omega t$.

The MAXIMUM value of voltage is reached twice each cycle and is the greatest value of instantaneous voltage generated during each cycle.

The ratio of the instantaneous value of voltage to the maximum value is equal to the sine of the angle corresponding to that instant.

AVERAGE VALUE OF VOLTAGE

The AVERAGE value of a sine wave of voltage or current is found by dividing the area under one alternation (half cycle) by the distance along the X axis between two successive instants (0° and 180°) corresponding to zero voltage. The average value is $\frac{2}{\pi}$, or 0.637, times the maximum. In the example in figure 8-5, the average voltage is

$$\frac{2}{\pi} \times 100, \text{ or } 63.7 \text{ volts.}$$

Thus,

$$E_{avg} = 0.637\ E_{max}$$

EFFECTIVE OR R.M.S. VALUE

The EFFECTIVE value of an a-c voltage or current of sine waveform is defined in terms of the equivalent heating effect of a direct current.

Heating effect is INDEPENDENT of direction of electron flow and varies as the square of the instantaneous current. Thus, an alternating current of sine waveform having a maximum value of 14.14 amperes produces the same amount of heat in a circuit having a resistance of 1 ohm that a direct current of 10 amperes produces. The effective value of this alternating current is equal to 0.707 of the maximum value. Thus, $I_{eff} = 0.707\ I_{max}$, or 0.707 x 14.14 = 10 amperes. The effective value is also known as the ROOT-MEAN-SQUARE (r.m.s.) value because it is the square root of the average of the squared values between zero and maximum. Thus an effective, or r.m.s. current of 10 amperes produces the same heating in a given resistance as a direct current of 10 amperes.

In practice, r.m.s. values of voltage and current are more important than instantaneous, maximum, or average values. Most a-c voltmeters and ammeters are calibrated in r.m.s. values. For example, suppose that an a-c voltmeter indicates that the effective voltage between the two conductors in a cable is 440 volts. Twice in each cycle the insulation is subject to a voltage stress that is $\frac{E_m}{E} = \frac{1}{0.707}$, or 1.41 times 440 volts, or 620 volts; where E_m is the maximum voltage and E is the r.m.s. value.

Suppose an a-c ammeter in the same circuit indicates an effective current of 10 amperes. Twice in each cycle the current exceeds this value by 41 percent but the average heating effect is that which a direct current of 10 amperes would produce. Thus, the conductor size is based on the ammeter indication (r.m.s. current) rather than on the maximum value, even though the insulation stress is always 41 percent higher than the voltmeter indication.

The ratio of the effective value to the average value of a wave is called the FORM FACTOR and for all sine waves is equal to $\frac{0.707}{0.637}$ or 1.11. The form factor for waveforms such as flattop waves is less than 1.11. For waveforms such as peaked waves the form factor is greater than 1.11. If a waveform is not that of a sine wave the constants for effective and average values do not apply. Most electrical power and lighting circuits have sine-wave currents and voltages and the effective values indicated by voltmeters and ammeters are appropriate.

Combining A-C Voltages

Vectors may be used to combine a-c voltages of sine waveform and of the same frequency. The angle between the vectors indicates the time difference between their positive maximum values. The length of the vectors represents either the effective value or the positive maximum value, as desired.

The sine wave voltages generated in coils a and b of the simple generators (fig. 8-6(A)) are 90° out of phase because the coils are located 90° apart on the two-pole armatures. The armatures are on a common shaft. When coil a is cutting squarely across the field, coil b is moving parallel to the field and not

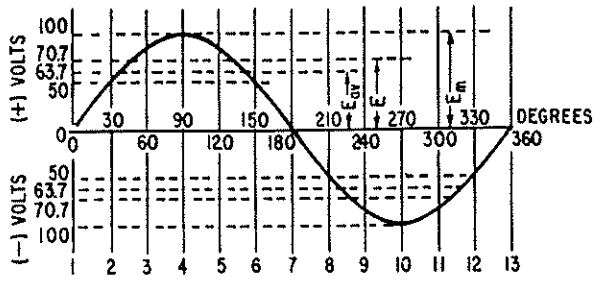


Figure 8-5.—Relative values of an a-c sine-wave voltage.

cutting through it. Thus, the voltage in coil *a* is maximum when the voltage in coil *b* is zero. If the frequency is 60 cycles per second, the time difference between the positive maximum values of these voltages is $\frac{90}{360} \times \frac{1}{60} = 0.00416$ second.

Vector E_a leads vector E_b by 90° in figure 8-6 (B) and sine wave *a* leads sine wave *b* by 90° in figure 8-6 (C). The curves are shown on separate axes to identify them with their respective generators; they are also projected on a common axis to show the relation between their instantaneous values. If coils *a* and *b* are connected in series and the maximum voltage generated in each coil is 10 volts, the total voltage is not 20 volts because the two maximum values of voltage do not occur at the same instant, but are separated one-fourth of a cycle. The voltages cannot be added arithmetically because they are out of phase. These values, however, can be added vectorially.

E_c in figure 8-6 (B) is the vector sum of E_a and E_b, and is the diagonal of the parallelogram, the sides of which are E_a and E_b. The effective voltage in each coil is 0.707 x 10 or 7.07 volts (where 10 volts is the maximum) and represents the length of the sides of the parallelogram. The effective voltage of the series combination is $7.07 \times \sqrt{2}$ or 10 volts and represents the length of the diagonal of the parallelogram.

Curve *c* in figure 8-6 (C) represents the sine wave variations of the total voltage E_c developed in the series circuit connecting coils *a* and *b*. Voltage E_a leads E_b by 90°. Voltage E_c lags E_a by 45°, and leads E_b by 45°.

Counterclockwise rotation of the vectors is considered positive rotation thus giving the sense of lead or lag. Thus, if E_a and E_b (fig. 8-6 (B)) are rotated counterclockwise, and their movement observed from a fixed position, E_a will pass this position first, then 90° later E_b will pass the position. Thus E_b lags E_a by 90°. If the maximum voltage in each coil is 10 volts, the maximum value of the combined voltage will be $10 \times \sqrt{2}$ or 14.4 volts. (See fig. 8-6 (C)).

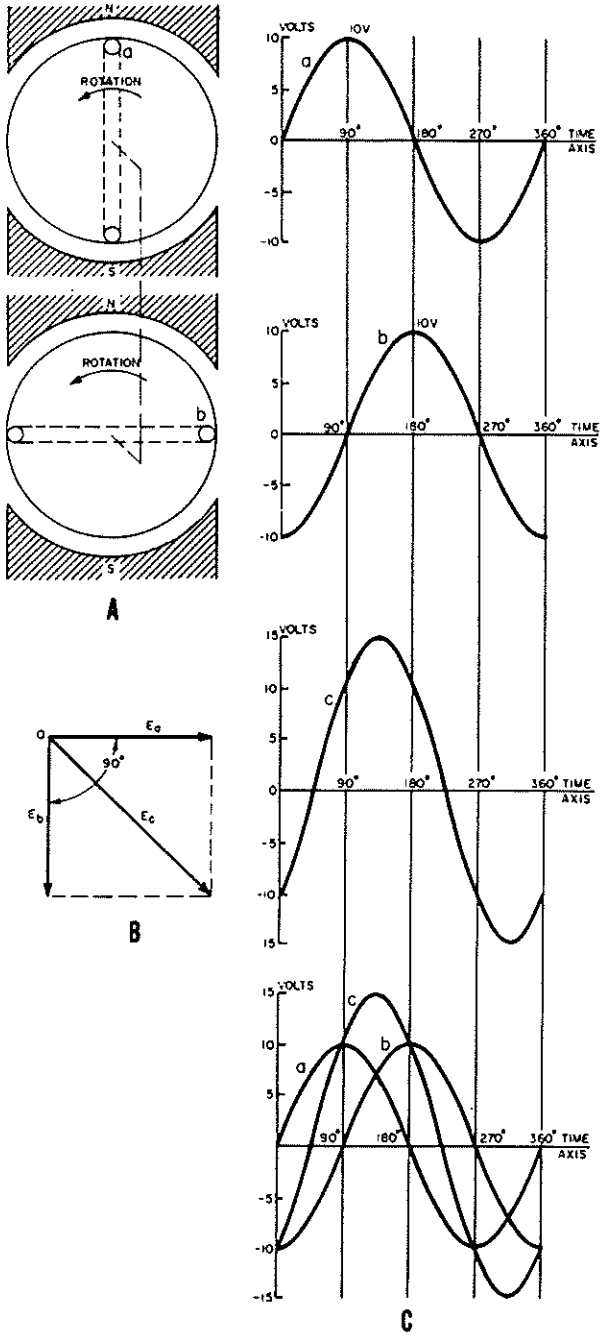


Figure 8-6.—Combining a-c voltages.

The important point to be made in this discussion is that two out-of-phase voltages may be resolved into a single resultant value by the use of vectors. Though generated voltages were used to illustrate the point in this case, the same rules apply to VOLTAGE DROPS as well. Any number of out-of-phase voltages may be combined vectorially, as long as they all have the same frequency; that is, as long as they remain a fixed number of degrees apart, like the two generator loops. Their magnitudes (LENGTH of their vectors) may be different. You will find vectors quite useful in the section of this course that deals with the effects of capacitors and inductors on a-c circuits. They are used to determine a-c impedances and currents, as well as voltages.

QUIZ

1. In formula form, angular velocity as applied to voltage or current is
   a. 2ω
   b. $2\pi\omega$
   c. $2\pi F$
   d. $2F$
2. How much larger is the maximum voltage value than the effective voltage value?
   a. 1.414
   b. 1.111
   c. 0.707
   d. 0.637
3. How many radians are in a complete circle?
   a. 0.707
   b. 1.11
   c. 3.14
   d. 6.28
4. Magnitude of a vector is denoted by the
   a. time axis
   b. length of the line
   c. length of the line, drawn to scale
   d. length of the time axis, drawn to scale
5. Which of the following best defines a cycle?
   a. One alternation
   b. Two alternations
   c. Three alternations
   d. Four alternations
6. The most important value associated with sine waves of voltage or current are
   a. instantaneous
   b. maximum
   c. average
   d. all of the above
7. The maximum value of a single sine wave of a-c voltage is 141.4 volts. What is the effective value?
   a. 63.7 volts
   b. 70.7 volts
   c. 99.97 volts
   d. 141.4 volts
8. Direction of a simple vector
   a. cannot be determined
   b. will indicate the reference point
   c. is indicated by an arrow at one end of the line
   d. is indicated by the magnitude
9. Frequency as applied to alternating current or voltage is the number of
   a. r.p.m. per second of time
   b. cycles per second of time
   c. poles per second of time
   d. volts generated per second of time
10. The effective value of an a-c voltage or current of sine waveform is defined in terms of the equivalent d.c.
    a. "voltage effect"
    b. "current effect"
    c. "heating effect"
    d. "cooling effect"
11. The average value of a single sine wave of a-c current is 63.7 amps. What is the r.m.s. value?
    a. 63.7 amps
    b. 70.7 amps
    c. 141.4 amps
    d. 156.95 amps
12. The instantaneous value of induced voltage of a single-phase generator (fig. 8-5)
    a. will never be zero
    b. depends on the sine of the angle
    c. will always be the same
    d. depends on the cosine of the angle
13. The period of a-c voltage of sine waveform is the time required for one complete
    a. r.p.m.
    b. alternation
    c. cycle
    d. degree
14. The "root-mean-square" value is also known as the
    a. average value
    b. peak value
    c. instantaneous value
    d. effective value
15. Two voltages of the same frequency "120 cycles per second" have their positive maximum values displaced by 90°. What is the time difference between the phases?
    a. 0.00208 sec.
    b. 0.00416 sec.
    c. 0.02080 sec.
    d. 0.04160 sec.

16. Positive rotation of a vector is
    a. clockwise
    b. counterclockwise
    c. either clockwise or counterclockwise
    d. neither clockwise nor counterclockwise
17. The effective generated voltage of a single-phase a-c generator may be obtained by the formula
    a. $E = 1.111 \quad \Phi \; fD10^{-8}$
    b. $E = 2.22 \quad \Phi \; fN^{-6}$
    c. $E = 1.111 \quad \Phi \; FD^{-6}$
    d. $E = 2.22 \quad \Phi \; fN10^{-8}$
18. Most a-c voltmeters and ammeters are calibrated in
    a. r.m.s. values
    b. average values
    c. peaks values
    d. instantaneous values
19. A radian is always equal to
    a. the circumference of the circle
    b. the radius of the circle
    c. pi
    d. 60 degrees
20. Angular velocity is symbolized by the Greek letter
    a. gamma γ
    b. mu μ
    c. omega ω
    d. beta β
21. If an active conductor's length is doubled, the
    a. pole length is cut in half
    b. flux per pole is cut in half
    c. generated voltage is doubled
    d. generated voltage is tripled
22. The "form factor" in most cases refers to the ratio of
    a. average value to maximum value
    b. instantaneous value to maximum value
    c. r.m.s. value to effective value
    d. r.m.s. value to average value
23. Conductor size in an a-c circuit is based on
    a. instantaneous current
    b. maximum current
    c. average current
    d. effective current
24. The term, "angular velocity," as applied to electricity refers to the number of
    a. radians per second a voltage vector rotates
    b. radians per minute a voltage vector rotates
    c. degrees averaged together
    d. degrees subtracted from the radians
25. Vectors indicate
    a. direction
    b. magnitude
    c. time, direction, and magnitude
    d. magnitude and direction
26. When voltages are out of phase, the total voltage can be found by adding
    a. arithmetically
    b. vectorially
    c. peaks values
    d. average values
27. The number of radians per second traversed by an alternating-voltage vector is closely related to its
    a. current sine wave
    b. voltage sine wave
    c. frequency
    d. none of the above

CHAPTER 9

INDUCTANCE AND CAPACITANCE

Inductance

Inductance is the property of an electric circuit that opposes any CHANGE IN THE CURRENT through that circuit. That is, if the current increases, a self-induced voltage opposes this change and delays the increase. If current decreases, a self-induced voltage tends to aid, or prolong the current flow, and delays the decrease. Thus, the most noticeable effect of inductance in a circuit is that current can neither increase nor decrease as fast in an inductive circuit as it can in a noninductive circuit.

The opposition to the current change is essentially an effect of electromagnetic induction, or induced e.m.f. In chapter 1 it was pointed out that a voltage is induced in a conductor whenever the conductor is moved across a magnetic field. The same thing also happens when the magnetic field is moved across the conductor. It is this relative motion between field and conductor that produces self-induced voltage in a conductor.

SELF-INDUCTANCE

Even a perfectly straight length of conductor has some inductance. As previously explained, current in a conductor always produces a magnetic field surrounding, or linking with, the conductor. When the current changes, the magnetic field changes, and an e.m.f. is induced in the conductor. This e.m.f. is called a SELF-INDUCED E.M.F. because it is induced in the conductor carrying the current. The direction of the induced e.m.f. has a definite relation to the direction in which the field that induces the e.m.f. varies. When the current in a circuit is increasing, the flux linking with the circuit is increasing. This flux cuts across the conductor and induces an e.m.f. in the conductor in such a direction as to oppose the increase in current and flux. Likewise, when the current is decreasing, an e.m.f. is induced in the opposite direction and opposes the decrease in current. These effects are summarized by Lenz's law, which states that THE INDUCED E.M.F. IN ANY CIRCUIT IS ALWAYS IN A DIRECTION TO OPPOSE THE EFFECT THAT PRODUCED IT.

The inductance is increased by shaping a conductor so that the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor. This is shown in its simplest form in figure 9-1 (A). A length of conductor is looped so that two portions of the conductor lie adjacent and parallel to one another. These portions are labeled conductor 1 and conductor 2. When the switch is closed, electron flow through the conductor establishes a typical concentric field around ALL portions of the conductor. For simplicity, however, the field is shown in a single plane that is perpendicular to both conductors. Although the field originates simultaneously in both conductors it is considered as originating in conductor 1 and its effect on conductor 2 will be noted. With increasing current, the field expands outward, cutting across a portion of conductor 2. The resultant induced e.m.f. in conductor 2 is shown by the dashed arrow. Note that it is in OPPOSITION to the battery current and voltage, according to Lenz's law.

The direction of this induced voltage may be determined by applying the Left-Hand Rule for Generators. This rule is applied to a portion of conductor 2 that is "lifted" and enlarged for the purpose in part (A) of figure 9-1. In applying this rule, the thumb of the left hand points in the direction that a conductor is moved through a field. (In this case, the field is moving, or expanding, in one direction, which is the same as the conductor moving in the opposite direction.) The index finger points in the direction of the

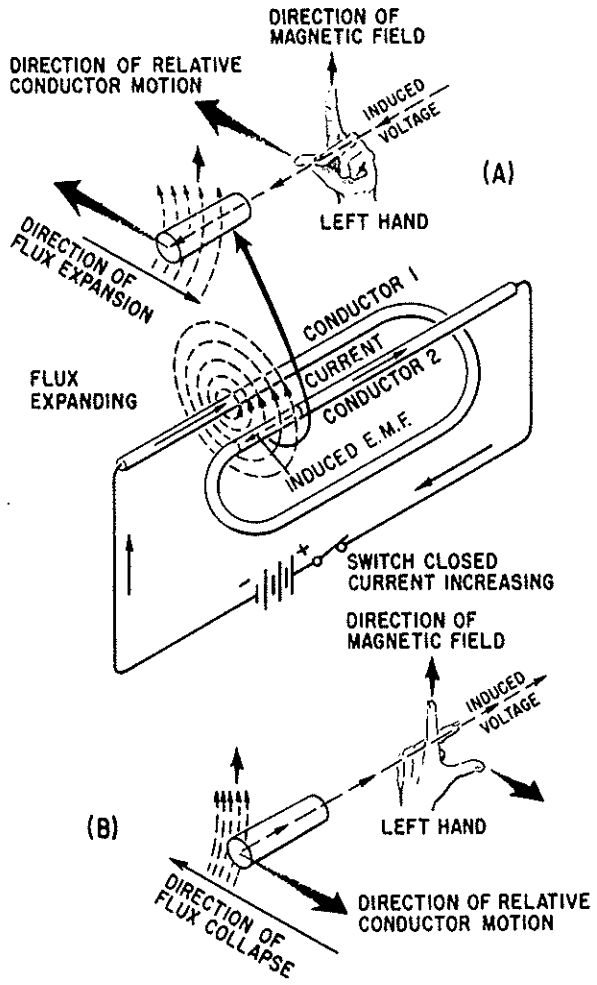


Figure 9-1.—Self-inductance.

magnetic field. The middle finger, extended as shown, will now indicate the direction of induced (generated) voltage.

In part (B), the same section of conductor 2 is shown, but with the switch opened and the flux collapsing. Applying the left-hand rule in this case shows that the reversal of flux MOVEMENT has caused a reversal in the direction of the induced voltage. The most important thing to note, however, is that the voltage of self-induction opposes both CHANGES in current. It delays the initial buildup of current by opposing the battery voltage, and delays the breakdown of current by exerting an induced voltage in the same direction that the battery voltage acted.

UNIT OF INDUCTANCE

The unit for measuring inductance, L, is the HENRY, h. An inductor has an inductance of 1 henry if an e.m.f. of 1 volt is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. The relation between the induced voltage, inductance, and rate of change of current with respect to time is stated mathematically as

$$E = L \frac{\Delta I}{\Delta t},$$

where E is the induced e.m.f. in volts, L is the inductance in henrys, and ΔI is the change in current in amperes occurring in Δt seconds. (Delta, symbol Δ, means "a change in . . . . . ")

The henry is a large unit of inductance and is used with relatively large inductors. The unit employed with small inductors is the millihenry, mh. For still smaller inductors the unit of inductance is the microhenry, μh.

FACTORS AFFECTING SELF-INDUCTANCE

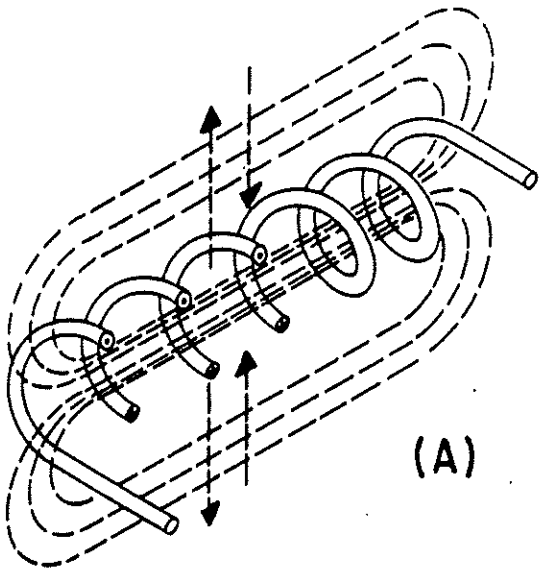
Many things affect the self-inductance of a circuit. An important factor is the degree of linkage between the circuit conductors and its electromagnetic flux. In a straight length of conductor, there is very little flux linkage between one part of the conductor and another. Therefore, its inductance is extremely small. Conductors become much more inductive when they are wound into coils, as shown in figure 9-2. This is true because there is maximum flux linkage between the conductor turns, which lie side by side in the coil.

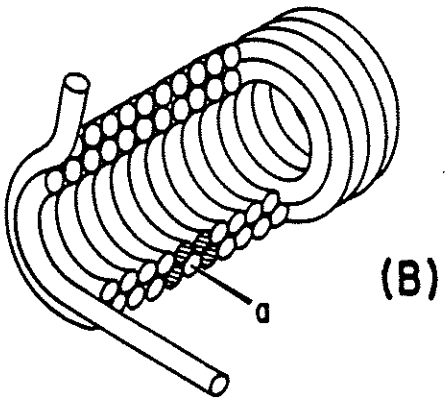
Inductance is further affected by the manner in which a coil is wound. The coil in figure 9-2 (A) is a poor inductor if compared to the others in the figure, because its turns are widely spaced, thus decreasing the flux linkage between its turns. Also, its lateral flux movement, indicated by the dashed arrows, does not link effectively, because there is only one layer of turns. A more inductive coil is shown in part (B). The turns are closely spaced, and the two layers link each other with a greater number of flux loops during all lateral flux movements. Note that nearly all turns, such as (a) are directly adjacent to four other turns (shaded), thus affording increased flux linkage.

The coil is made still more inductive by winding it in three layers, and providing a highly

permeable core, as in figure 9-2 (C). The increased number of layers (cross-sectional area) improves lateral flux linkage. Note that some turns, such as (b) lie directly adjacent to six other turns (shaded). The magnetic properties of the iron core increase the total coil flux strength many times that of an air core coil of the same number of turns.

From the foregoing, it can be seen that the primary factors controlling the inductance of a coil are (1) the number of turns of conductor, (2) the ratio of the cross-sectional area of the coil to its length, and (3) the permeability of its core material. The inductance of a coil is affected by the magnitude of current when the core is a magnetic material. When the core is air, the inductance is independent of the current.





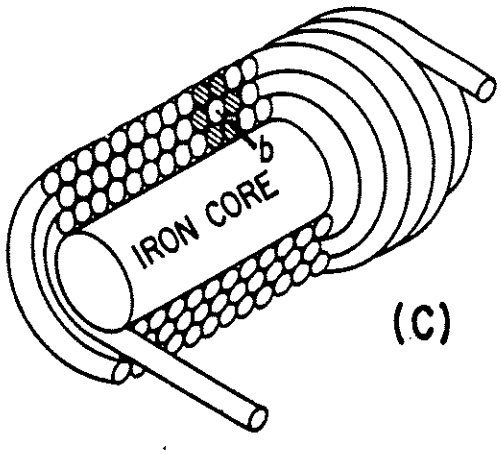


Figure 9-2.—Coils of various inductances.

GROWTH AND DECAY OF CURRENT IN AN R-L SERIES CIRCUIT

If a battery is connected across a pure inductance, the current builds up to its final value at a rate that is determined by the battery voltage and the internal resistance of the battery.

The current buildup is gradual because of the counter e.m.f. generated by the self-inductance of the coil. When the current starts to flow, the magnetic lines of force move out, cut the turns of wire on the inductor, and build up a counter e.m.f. that opposes the e.m.f. of the battery. This opposition causes a delay in the time it takes the current to build up to steady value. When the battery is disconnected, the lines of force collapse, again cutting the turns of the inductor and building up an e.m.f. that tends to prolong the current flow.

A voltage divider containing resistance and inductance may be connected in a circuit by means of a special switch, as shown in figure 9-3 (A). Such a series arrangement is called an *R-L* series circuit.

If switch *S1*, is closed (as shown), a voltage, *E*, appears across the divider. A current attempts to flow, but the inductor opposes this current by building up a back e.m.f. that, at the initial instant, exactly equals the input voltage, *E*. Because no current can flow under this condition, there is no voltage across resistor *R*. Figure 9-3 (B) shows that all of the voltage is impressed across *L* and no voltage appears across *R* at the instant switch *S1* is closed.

As current starts to flow, a voltage, e_γ, appears across *R*, and e_L is reduced by the same amount. The fact that the voltage across *L* is reduced means that the growth current, i_g, is increasing and censequently e_γ is increasing. Figure 9-3 (B) shows that e_L finally becomes zero when i_g stops increasing, while e_γ builds up to the input voltage, *E*, as i_g reaches its maximum value. Under steady-state conditions, only the resistor limits the size of the current.

Electrical inductance is like mechanical inertia, and the growth of current in an inductive circuit can be likened to the acceleration of a boat on the surface of the water. The boat begins to move at the instant a constant force is applied to it. At this instant its rate of change of speed (acceleration) is greatest, and all the applied force is used to overcome the inertia of the boat. After a while the speed of the boat increases (its acceleration decreases) and the applied force is used up in overcoming the friction of the water against the hull. As the speed levels off and the acceleration becomes zero, the applied force equals the opposing friction force at this speed and the inertia effect disappears.

When the battery switch in the *R-L* circuit of figure 9-3 (A) is closed, the rate of current

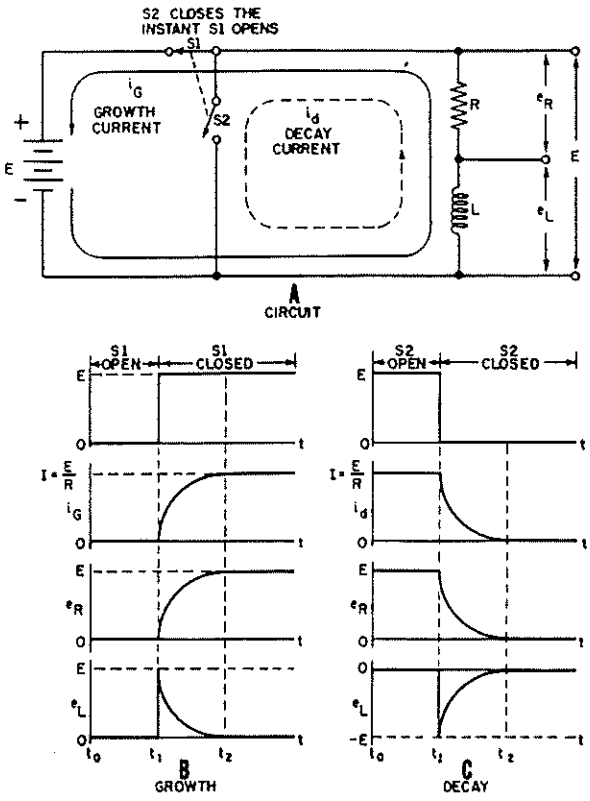


Figure 9-3.—Growth and decay of current in an R-L series circuit.

increase is maximum in the inductive circuit. At this instant all the battery voltage is used in overcoming the e.m.f. of self-induction which is a maximum because the rate of change of current is maximum. Thus the battery voltage is equal to the drop across the inductor and the voltage across the resistor is zero. As time goes on more of the battery voltage appears across the resistor and less across the inductor. The rate of change of current is less and the induced e.m.f. is less. As the steady-state condition of the current flow is approached the drop across the inductor approaches zero and all of the battery voltage is used to overcome the resistance of the circuit.

Thus the voltage across the inductor and resistor change in magnitudes during the period of growth of current the same way the force applied to the boat divides itself between the inertia and friction effects. In both examples, the force is developed first across the inertia-inductive effect and finally across the friction-resistive effect.

If switch $S2$ is closed (source voltage E removed from the circuit), the flux that has been established around L collapses through the windings and induces a voltage, e_L, in L that has a polarity opposite to E and essentially equal to it in magnitude. The induced voltage, e_L, causes current i_d to flow through R in the same direction that it was flowing when $S1$ was closed. A voltage, e_r, that is initially equal to E, is developed across R. It rapidly falls to zero as the voltage, e_L, across L, due to the collapsing flux, falls to zero.

Mutual Inductance

MUTUAL INDUCTANCE DEFINED

Whenever two coils are located so that the flux from one coil links with the turns of the other, a change of flux in one coil will cause an e.m.f. to be induced in the other coil. The two coils have MUTUAL INDUCTANCE. The amount of mutual inductance depends on the relative position of the two coils. If the coils are separated a considerable distance, the amount of flux common to both coils is small and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flux of one coil links the turns of the other the mutual inductance is high. The mutual inductance can be increased greatly by mounting the coils on a common iron core.

Two coils placed close together with their axes in the same plane are shown in figure 9-5. Coil A is connected to a battery through switch S, and coil B is connected to galvanometer G. When the switch is closed (fig. 9-5 (A)), the current that flows in coil A sets up a magnetic field that links coil B, causing an induced current and a momentary deflection of galvanometer G. When the current in coil A reaches a steady value, the galvanometer returns to zero. If the switch is opened (fig. 9-5 (B)), the galvanometer deflects momentarily in the opposite direction, indicating a momentary flow of current in the opposite direction in coil B. This flow of current in coil B is caused by the e.m.f. induced in coil B, which is produced by the collapsing flux of coil A.

When current flows through coil A the flux expands in coil A producing a north pole nearest coil B. Some of the flux, that expands from left to right, cuts the turns of coil B. This flux induces an e.m.f. and current in coil B that opposes the growth of current and flux in coil A. Thus the current in B tries to establish a north pole nearest coil A (like poles repel).

When the switch is opened, the magnetic field produced by coil A collapses. The collapse of the flux cuts the turns of coil B in the opposite direction and produces a south pole nearest coil A (unlike poles attract). This polarity aids the magnetism of coil A, tending to prevent the collapse of its field.

FACTORS AFFECTING MUTUAL INDUCTANCE

The mutual inductance of two adjacent coils is dependent upon the—(1) physical dimensions of the two coils, (2) number of turns in each coil, (3) distance between the two coils, (4) relative positions of the axes of the two coils, and (5) the permeability of the cores.

If the two coils are positioned so that all the flux of one coil cuts all the turns of the other, the mutual inductance can be expressed as follows:

$$M = \frac{0.4\pi\mu SN_1N_2}{10^8 l}$$

where M equals mutual inductance of coils in henrys
N_1 and N_2 equal the number of turns in coils 1 and 2 respectively
S equals area of core in square cm.
μ equals permeability of core
l equals length of core in cm.

If the two coils are so positioned with respect to each other that all the flux of one coil cuts all the turns of the other, the coils have UNITY COEFFICIENT OF COUPLING. If all of the flux produced by one of the coils cuts only one-half the turns of the other coil, the coefficient of coupling is 0.5. Coefficient of coupling is designated by the letter, K. The coefficient of coupling is equal to the percentage of flux originating in one coil that cuts the other coil. It is never exactly equal to unity but it approaches this value in certain shell-type transformers.

The mutual inductance between two coils, $L1$ and $L2$, may be expressed in terms of the inductance of each coil and the coefficient of coupling, K, as follows,

$$M = K\sqrt{L_1 L_2},$$

where M is in the same units of inductance as $L1$ and $L2$.

EFFECTS OF INDUCTANCE IN AN ELECTRIC CIRCUIT

Reaction of an Inductor to Flux Change

Up to this point, the effects of inductance in an electric circuit have been considered as being controlled only by the particular inductor considered in each case. For instance, the time required for the growth and decay of current in the circuit shown in figure 9-3 is determined only by the inherent properties of the inductor L, namely, the ratio of its inductance to its resistance. When permitted to change at this inherent, or natural rate, the shape of the L/R curve for any particular inductor will always remain the same. That is, it will always exhibit the same natural opposition to any change in current and flux, when left to its own tendencies. At this point, however, it must be pointed out that an inductor can be made to exhibit many different degrees of reaction. This is done by using external means to change the flux linking the inductor. These changes, such as variations in the applied frequency, usually do not occur at the same rate as the inductor's inherent rate. When the flux is changed RAPIDLY by some external means, the inductor's reaction is much greater than when the flux is changed gradually. That is, the inductor's self-induced e.m.f. is dependent on the RATE with respect to time at which the linking flux is changed.

The dependence of the induced voltage on the rate of change of flux with respect to time is shown by means of the simple apparatus in

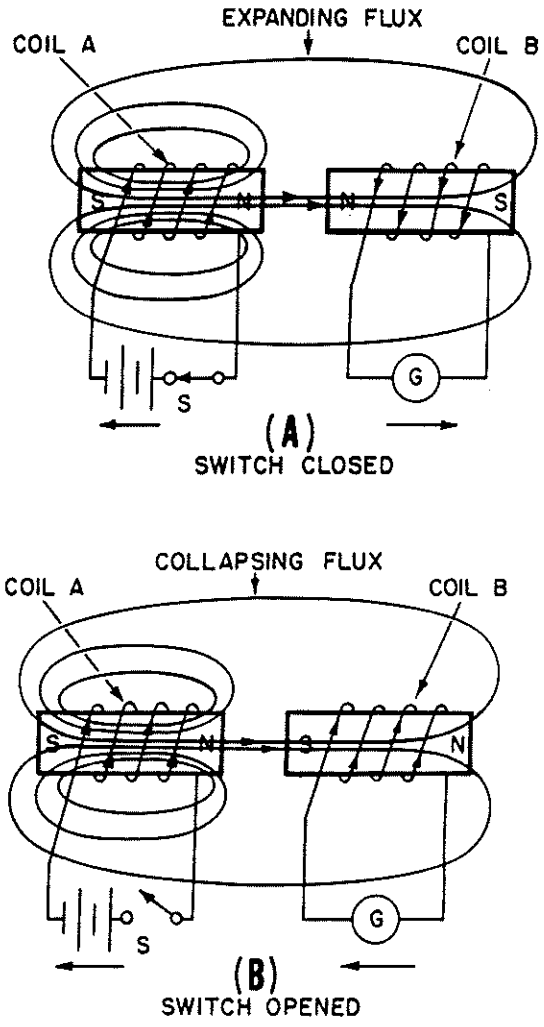


Figure 9-5.—Mutual inductance.

figure 9-6. When the switch is closed, current builds up to a maximum, and the lamp glows with its normal brilliance. If the iron core is inserted rapidly into the coil, the flux increases rapidly (because of the increased inductance of the coil), and the induced voltage opposes, according to Lenz's law, the source voltage. Therefore, less current flows through the lamp, and it dims momentarily. If the core is withdrawn rapidly from the coil, a portion of the flux that was established around the coil collapses. The resulting induced voltage opposes the decrease (again, according to Lenz's law) by aiding the source voltage, and the coil current increases. Consequently, the lamp burns brighter momentarily. The faster the iron core is moved the greater is the flux change per unit of time and the more noticeable is the effect on the lamp.

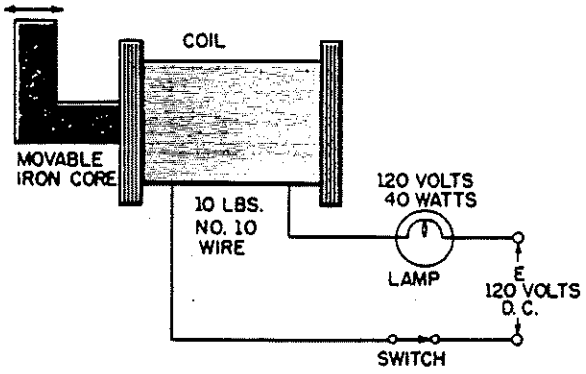


Figure 9-6.—Dependence of self-induced voltage on the rate of change of flux.

Effects of Inductance in an A-C Circuit

When a circuit containing a coil is energized with direct current, the coil's effect in the circuit is evident only when the circuit is energized, or when it is deenergized. For instance, when the switch in figure 9-7 is placed in position ①, the inductance of coil *L* will cause a delay in the time required for the lamps to attain normal brilliance. After they have attained normal brilliance, the inductance has no effect on the circuit as long as the switch remains closed. When the switch is opened, an electric spark will jump across the opening switch contacts. The e.m.f. which produces the spark is caused by the collapsing magnetic field cutting the turns of the inductor.

When the inductive circuit is supplied with alternating current, however, the inductor's effect is continuous and much greater than when it was supplied with direct current. For equal applied voltages, the current through the circuit is less when a. c. is applied than when d. c. is applied, as may be demonstrated by the circuits of figure 9-7. The alternating current is accompanied by an alternating magnetic field around the coil, which cuts through the turns of the coil. This action induces a voltage in the coil that always opposes the changing current. When the switch is in position ① the lamps burn brightly on direct current but in position ②, although the effective value of the applied a-c voltage is equal to the d-c value, the lamps burn dimly because of the opposition developed across the inductance. Most of the applied voltage appears across *L*, with little remaining for the lamps.

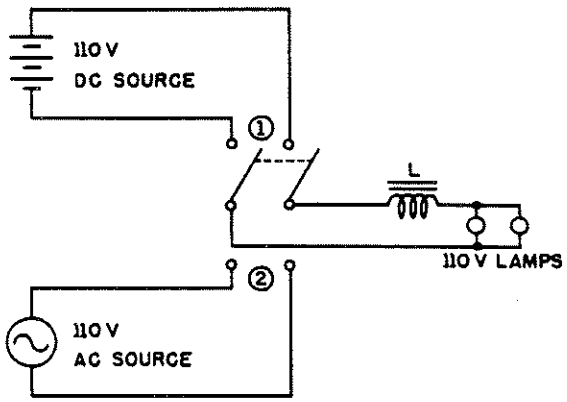


Figure 9-7.—Relative effects of inductance in d-c and a-c circuits.

Relation Between Induced Voltage and Current

As stated previously, any change in current, either a rise or a fall, in a coil causes a corresponding change of the magnetic flux around the coil (fig. 9-8, (A)). If the current is sinusoidal, the induced voltage will also have the form of a sine wave. Because the current changes at its maximum rate when it is going through its zero value at 0°, 180°, and 360° (fig. 9-8 (B)), the flux change is also greatest at those times. Consequently, the self-induced voltage in the coil is at its maximum value at these instants. According to Lenz's law, the induced voltage always opposes the change in current. Thus, when the current is rising in a positive direction at 0°, the induced e.m.f. is of opposite polarity to the impressed e.m.f. and opposes the rise

in current. Later, when the current is falling toward its zero value at 180°, the induced voltage is of the same polarity as the current and tends to keep the current from falling. Thus the induced voltage can be seen to lag the current by 90°. The resistance of the coil is small and the principal opposition to the current flow through the coil is the induced voltage, E_{ind}. The applied voltage, E, is slightly larger than E_{ind} and diametrically opposed to it, as indicated in the vector diagram (fig. 9-8 (C)).

The current lags the applied voltage in an inductive circuit by an angle of 90° and leads the induced voltage by 90°. The induced voltage is always of opposite polarity to the applied voltage and is called a COUNTER E.M.F. or a BACK E.M.F. because it always opposes the change of current.

Capacitance

Capacitance is the property of an electric circuit that resists, or opposes, any CHANGE OF VOLTAGE in the circuit. That is, if applied voltage is increased, capacitance opposes the change and delays the voltage increase across the circuit. If applied voltage is decreased, capacitance tends to maintain the higher original voltage across the circuit, thus delaying a decrease. Consequently, the most noticeable effect of capacitance in a circuit is that voltage can neither increase nor decrease as fast in a capacitive circuit as it can in a noncapacitive circuit. Capacitance is also defined as that property of a circuit that enables energy to be stored in an electric field.

THE CAPACITOR

Figure 9-9 depicts a capacitor in its simplest form. It consists of two metal plates separated by a thin layer of insulating material (dielectric). When connected to a voltage source (battery) as shown, the voltage forces electrons onto one plate, making it negative, and pulls them off the other, making it positive. Electrons cannot flow through the dielectric. Since it takes a definite quantity of electrons to "fill up," or charge, a capacitor, it is said to have a CAPACITY. This characteristic is referred to as CAPACITANCE.

The basic action of a capacitor is illustrated in figure 9-10. In part (A), the capacitor is in a balanced, or uncharged, condition. When the switch is set to position 1, in part (B), a surge of battery current immediately charges the capacitor. The natural tendency of the capacitor is to restore its own balance by discharging through the battery in a counterclockwise direction. This tendency is small at first, but grows as the capacitor is charging.

This characteristic is commonly referred to as a counter e.m.f., since it is actually a voltaic force. When the capacitor's counter e.m.f. has risen to equal the battery voltage, the capacitor is said to be charged, and current is zero. When the charge is completed, the switch is placed back to position 2, as shown in figure 9-10 (C).

In this condition, the capacitor is a source of potential energy, similar to a charged battery. Its charged plates exert a voltage between terminals 2 and 3 of the switch. In addition, an electrostatic field, or force, exists between the plates, acting through the dielectric. This is an actual physical force, evidenced by the mutual attraction of the unlike charges, and the dielectric must be structurally strong enough to withstand it. The dielectric must also have sufficient insulating qualities to withstand the potential differences. When the switch is placed in position 3, the capacitor discharges, thus rebalancing itself. As the potential difference of the plates goes to zero, their charges are equalized, and the electrostatic force is relaxed.

Two facts should be noted in connection with figure 9-10 (B):

1. After a momentary surge of electrons, direct current is completely stopped by the capacitor.
2. Free electrons do not pass from one plate to the other through the dielectric because the dielectric is a nonconductor.

The electrons are distributed on the negative plate and held there by the mutual attraction of the corresponding positive charges on the positive plate. The presence of the two polarities (plus and minus) establishes the electric field through the dielectric.

The electric lines of force (flux) originate on the negatively charged plate and terminate on the positively charged plate. In other words,

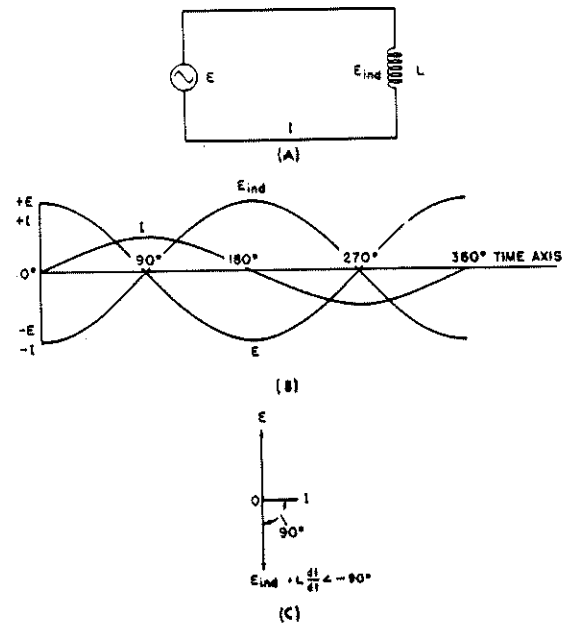


Figure 9-8.—Relation between induced voltage and current.

the lines are assumed to follow the same paths that UNIT NEGATIVE CHARGES would take if they were free to move. The lines of force would be present even if the plates were enclosed in a perfect vacuum. Electric lines of force cannot exist in a metallic conductor to any great extent, because equalizing currents are free to flow within the metal. If the force is to exist, two dissimilarly charged bodies must be separated by a nonconductor.

DIELECTRIC MATERIALS

Various materials differ in their ability to support electric flux or to serve as dielectric material for capacitors. This phenomenon is somewhat similar to permeability in magnetic circuits. Dielectric materials, or insulators are rated in their ability to support electric flux in terms of a figure called the DIELECTRIC CONSTANT. The higher the value of dielectric constant (other factors being equal), the better is the dielectric material.

Dry air is the standard dielectric for purposes of reference and is assigned the value of unity (or one). The dielectric constant of a dielectric material is also defined as the ratio of the capacitance of a capacitor having that particular material as the dielectric to the capacitance of the same capacitor having air as the dielectric. By way of comparison, the dielectric constant of pure water is 81; flint glass, 9.9; and paraffin paper, 3.5. The range of dielectric constants is much more restricted than is the range of permeabilities. Average dielectric constants for some common materials is given in the following list.

Material	Dielectric-constant (Average values)
Air	1
Polystyrene	2.5
Paraffin paper	3.5
Mica	6
Flint glass	9.9
Methyl alcohol	35
Glycerin	56.2
Pure water	81

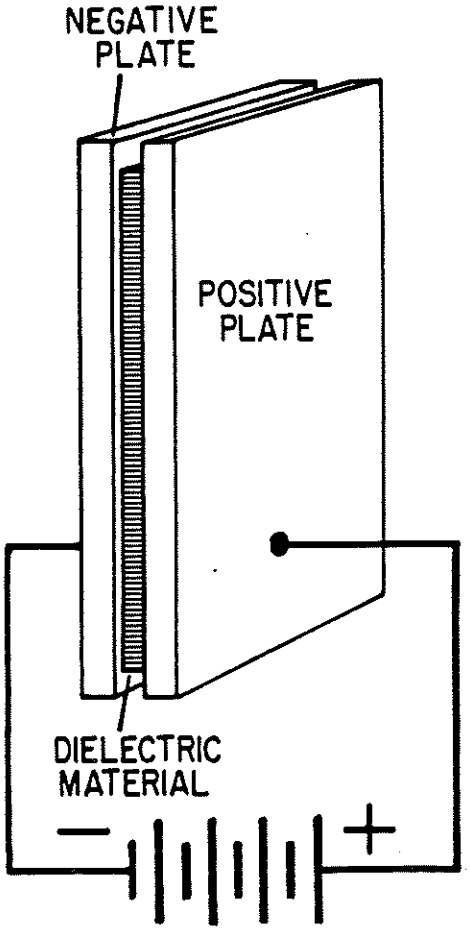


Figure 9-9.—Simple capacitor.

UNIT OF CAPACITANCE

The capacitance of a capacitor is proportional to the quantity of charge that can be stored in it for each volt applied across its plates. A capacitor possesses a capacitance of 1 FARAD when a quantity of charge of 1 coulomb imparted to it raises its potential 1 volt (1 coulomb is equal to 6.28×10^{18} electrons). The relation between capacitance, charge, and voltage is the basic formula of the capacitor, and may be stated as follows:

$$C = \frac{Q}{E},$$

where C is the capacitance in farads, Q the quantity of charge in coulombs, and E the difference in potential in volts.

A capacitor with a value of 1 farad would be of enormous dimensions. Hence, use of the farad as a unit is usually limited to definition and calculations. The practical units of capacitance are the microfarad (μf.) and the micromicrofarad ($\mu\mu$f.). A capacitor whose value is 1 microfarad is one in which a microcoulomb (6.28×10^{12} electrons) is stored when 1 volt is applied across its plates.

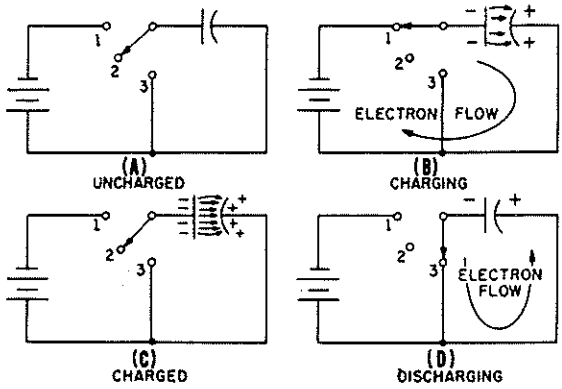


Figure 9-10.—Capacitor action.

FACTORS AFFECTING THE VALUE OF CAPACITANCE

The capacitance of a capacitor depends on the three following factors:

1. The area of the plates.
2. The distance between the plates.
3. The dielectric constant of the material between the plates.

CHARGE AND DISCHARGE OF AN R-C SERIES CIRCUIT

Ohm's law states that the voltage across a resistance is equal to the current through it times the value of the resistance. This means that a voltage will be developed across a resistance ONLY WHEN CURRENT FLOWS through it.

A capacitor is capable of storing or holding a charge of electrons. When uncharged, both

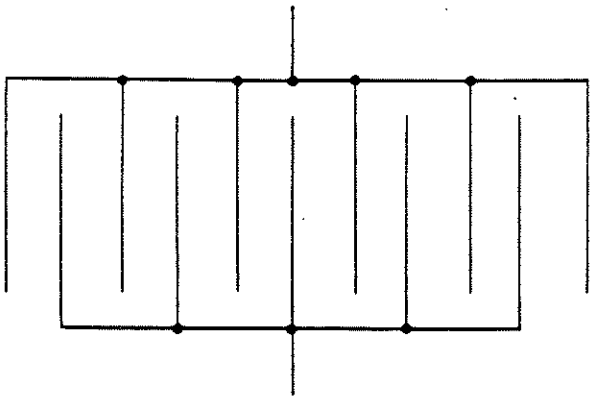


Figure 9-11.—Capacitor multiple-plate construction.

plates contain the same number of free electrons. When charged, one plate contains more free electrons than the other. The difference in the number of electrons is a measure of the charge on the capacitor. The accumulation of this charge builds up a voltage across the terminals of the capacitor, and the charge continues to increase until this voltage equals the applied voltage. The charge in a capacitor is related to the capacitance and voltage as follows:

$$Q = CE,$$

in which Q is the charge in coulombs, C the capacitance in farads, and E the difference in potential in volts. Thus, the greater the voltage, the greater the charge on the capacitor. Unless a discharge path is provided, a capacitor keeps its charge indefinitely. Any practical capacitor, however, has some leakage through the dielectric so that the charge will gradually leak off.

A voltage divider containing resistance and capacitance may be connected in a circuit by means of a switch, as shown in figure 9-12 (A). Such a series arrangement is called an R-C series circuit.

If S1 is closed, electrons flow counterclockwise around the circuit containing the battery, capacitor, and resistor. This flow of electrons ceases when C is charged to the battery voltage. At the instant current begins to flow, there is no voltage on the capacitor and the drop across R is equal to the battery voltage. The initial charging current, I, is therefore equal to $\frac{E_S}{R}$. Figure 9-12 (B) shows that at the instant the switch is closed, the

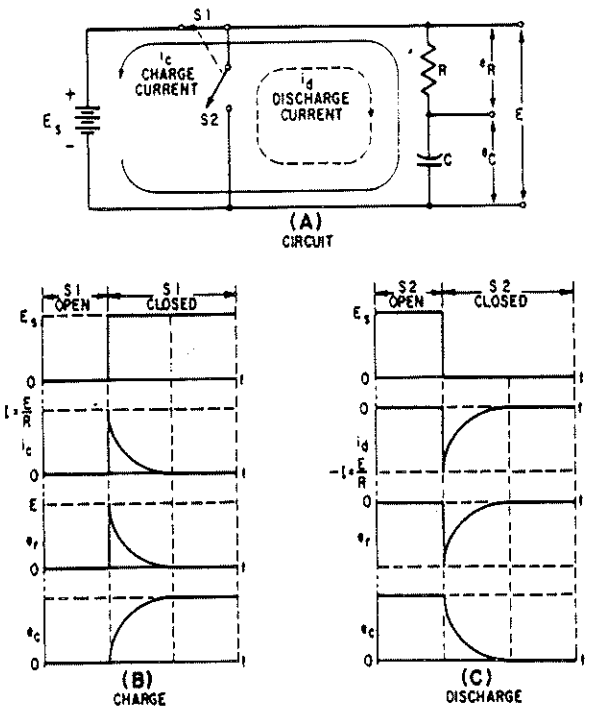


Figure 9-12.—Charge and discharge of an R-C series circuit.

entire input voltage, E_S, appears across R, and that the voltage across C is zero.

The current flowing in the circuit soon charges the capacitor. Because the voltage on the capacitor is proportional to its charge, a voltage, e_C, will appear across the capacitor. This voltage opposes the battery voltage—that is, these two voltages buck each other. As a result, the voltage e_γ across the resistor is E_S-e_C, and this is equal to the voltage drop $(i_C R)$ across the resistor. Because E_S is fixed, i_C decreases as e_C increases.

The charging process continues until the capacitor is fully charged and the voltage across it is equal to the battery voltage. At this instant, the voltage across R is zero and no current flows through it. Figure 9-12 (B) shows the division of the battery voltage, E_S, between the resistance and capacitance at all times during the charging process.

If S2 is closed (S1 opened) in figure 9-12 (A), a discharge current, i_d, will discharge the capacitor. Because i_d is opposite in direction to i_C, the voltage across the resistor will have a polarity opposite to the polarity during the

charging time. However, this voltage will have the same magnitude and will vary in the same manner. During discharge the voltage across the capacitor is equal and opposite to the drop across the resistor, as shown in figure 9-12 (C). The voltage drops rapidly from its initial value and then approaches zero slowly, as indicated in the figure.

VOLTAGE RATING OF CAPACITORS

In selecting or substituting a capacitor for use in a particular circuit, you must consider (1) the value of capacitance desired, and (2) the amount of voltage to which the capacitor is to be subjected. If the voltage applied across the plates is too great, the dielectric will break down and arcing will occur between the plates. The capacitor is then short-circuited and the possible flow of direct current through it can cause damage to other parts of the equipment. Capacitors have a voltage rating that should not be exceeded.

The working voltage of the capacitor is the maximum voltage that can be steadily applied without danger of arc-over. The working voltage depends on (1) the type of material used as the dielectric, and (2) the thickness of the dielectric.

The voltage rating of the capacitor is a factor in determining the capacitance because capacitance decreases as the thickness of the dielectric increases. A high-voltage capacitor that has a thick dielectric must have a larger plate area in order to have the same capacitance as a similar low-voltage capacitor having a thin dielectric. The voltage rating also depends on frequency because the losses, and the resultant heating effect, increase as the frequency increases.

A capacitor that may be safely charged to 500 volts d.c. cannot be safely subjected to alternating or pulsating direct voltages whose effective values are 500 volts. An alternating voltage of 500 volts (r.m.s.) has a peak voltage of 707 volts, and a capacitor to which it is applied should have a working voltage of at least 750 volts. The capacitor should be selected so that its working voltage is at least 50 percent greater than the highest voltage to be applied to it.

CAPACITOR TYPES

Capacitors may be divided into two major groups—fixed and variable.

Fixed Capacitors

Fixed Capacitors are constructed in such manner that they possess a fixed value of capacitance which cannot be adjusted. They may be classified according to the type of material used as the dielectric, such as paper, oil, mica, and electrolyte.

Paper Capacitors.—The plates of paper capacitors are made of strips of metal foil. These are separated by waxed paper. The capacitance of paper capacitors ranges from about 200 micromicrofarads to several microfarads. The strips of foil and paper are rolled together to form a cylindrical cartridge, which is then sealed in wax to keep out moisture and to prevent corrosion and leakage. Two metal leads are soldered to the plates, one extending from each end of the cylinder. Some paper capacitors may have one terminal (lead) marked GROUND, which means that this terminal connects to the outside foil of the capacitor.

Many different kinds of outer covering are used for paper capacitors, the simplest being a tubular cardboard. Some types of paper capacitors are encased in a mold of very hard plastic; these types are very rugged and may be used over a much wider temperature range than the cardboard-case type. Figure 9-16 (A) shows the construction of a tubular paper capacitor; part (B) shows a completed cardboard encased capacitor.

Bathtub-type capacitors consist of paper-capacitor cartridges hermetically sealed in metal containers. (See fig. 9-16 (C)). The container often serves as a common terminal for several enclosed capacitors. It always serves as a shield against electrical interference.

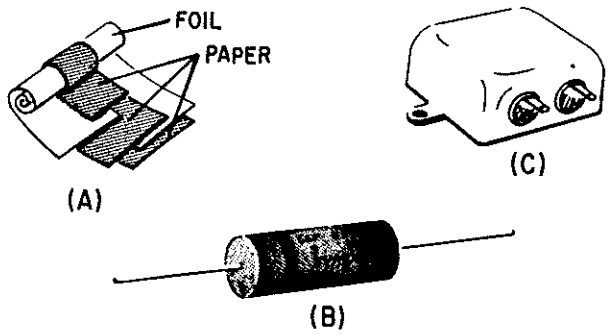


Figure 9-16.—Paper capacitor.

Oil Capacitors.—In radio and radar transmitters, voltages high enough to cause arcing, or breakdown, of paper dielectrics are often employed. Consequently, in these applications capacitors that have oil or oil-impregnated paper as the dielectric material are preferred. Capacitors of this type are considerably more expensive than ordinary paper capacitors and their use is generally restricted to radio and radar transmitting equipment.

Mica Capacitors.—The fixed mica capacitor is made of metal foil plates that are separated by sheets of mica, which form the dielectric. The whole assembly is covered in molded plastic. By molding the capacitor parts into a plastic case, corrosion and damage to the plates and dielectric are prevented in addition to making the capacitor mechanically strong. Various types of terminals are used to connect mica capacitors into circuits; these are also molded into the plastic case.

Mica is an excellent dielectric and will withstand higher voltages than paper without allowing arcing between the plates. Common values of mica capacitors range from approximately 50 micromicrofarads to about 0.02 microfarad. Some typical mica capacitors are shown in figure 9-17.

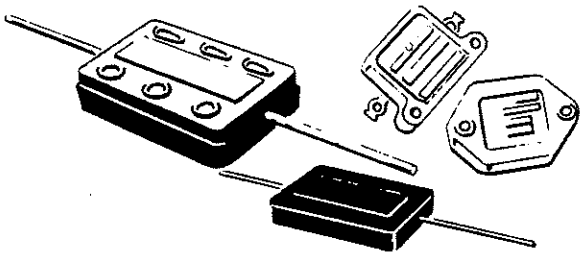


Figure 9-17.—Typical mica capacitors.

Electrolytic Capacitors.—For capacitances greater than a few microfarads, the physical size of a paper or a mica capacitor becomes excessive. Electrolytic capacitors are used for values of capacitance ranging from 1 to 1,500 microfarads. These capacitors provide large capacitance in small physical sizes. Unlike the other types, electrolytic capacitors are generally polarized, and should be subjected to direct voltage, or pulsating direct voltage only; however, a special type of electrolytic capacitor is made for use in alternating-current motors. Remember that unless an electrolytic is designed for use on a.c., it must always be connected in accordance with its polarity markings.

The electrolytic capacitor is widely used in electronic circuits, and consists of two metal plates separated by an electrolyte. The electrolyte, either in paste or liquid form, is in contact with the negative terminal and this combination comprises the negative electrode. The dielectric is an exceedingly thin film of oxide deposited on the positive electrode of the capacitor. The positive electrode is an aluminum sheet, and it is folded so as to achieve maximum area. The capacitor is subjected to a forming process during manufacture, in which current is passed through it. The flow of current results in the deposit of the thin coating of oxide on the aluminum plate. The close spacing of the negative and positive electrodes gives rise to the comparatively high capacitance value. However, it allows greater possibility of voltage breakdown and leakage of electrons from one electrode to the other.

Two kinds of electrolytic capacitors are in use—wet-electrolytic and dry-electrolytic. In the former, the electrolyte is a liquid and the container must be leakproof. This type should always be mounted in a vertical position.

The electrolyte of the dry-electrolytic unit is a paste contained in a separator made of absorbent material such as gauze or paper. The separator serves to hold the electrolyte in place, and also prevents short-circuiting the plates. Dry-electrolytic capacitors are made in both cylindrical and rectangular form and may be contained either within cardboard or metal covers. Since the electrolyte cannot spill, the dry capacitor may be mounted in any convenient position. Some typical electrolytic capacitors are shown in figure 9-18.

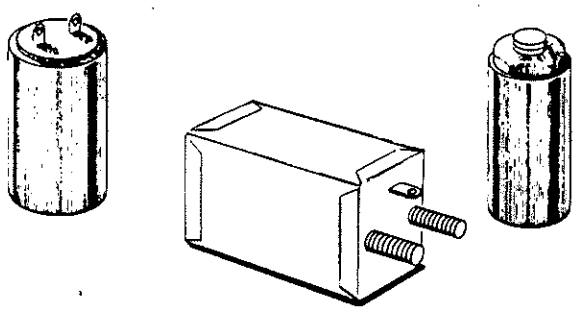


Figure 9-18.—Typical electrolytic capacitors.

Variable Capacitors

Variable capacitors are constructed in such manner that their value of capacitance can be varied. A typical variable capacitor (adjustable capacitor) is the rotor/stator type. It consists of two sets of metal plates that are arranged so that the rotor plates move between the stator plates. Air is the dielectric. As the position of the rotor is changed, the capacitance value is likewise changed. This is the type capacitor used for tuning most radio receivers and it is shown in figure 9-19 (A). Another type variable (trimmer) capacitor is shown in figure 9-19 (B); it consists of two plates separated by a sheet of mica. A screw adjustment is used to change the distance between the plates, thereby changing the capacitance.

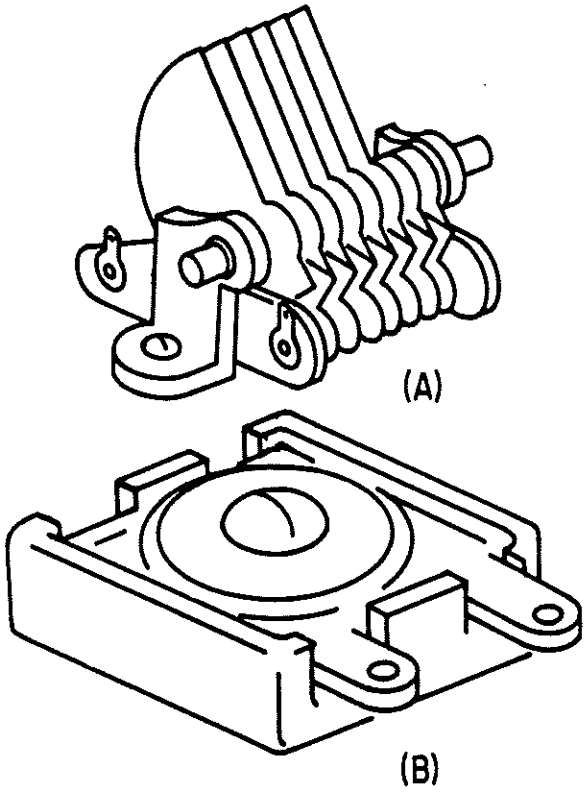


Figure 9-19.—Variable capacitors.

Ceramic Capacitors

A relatively new type capacitor that may be constructed as either fixed or variable is the ceramic. Ceramic capacitors usually range in value between 1 micromicrofarad and 0.01 microfarad. Ceramic is used as the dielectric and film deposits of silver are used for the plates. These capacitors are small in physical size and are constructed in various shapes. Typical capacitors are shown in figure 9-20.

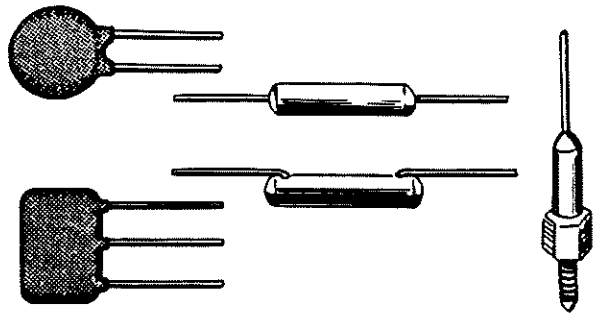


Figure 9-20.—Ceramic capacitors.

QUIZ

1. Inductance is the property of an electric circuit that
   a. opposes any change in the applied voltage through that circuit
   b. opposes any change in thecurrent through that circuit
   c. aids any change in the applied voltage through that circuit
   d. aids any change in the current through that circuit
2. A coil has a resistance of 22 ohms, and in 0.1 second after the switch is closed, the current has reached 63.2% of its final value. The value of inductance (L) is
   a. 0.22 henries
   b. 0.44 henries
   c. 2.20 henries
   d. 4.40 henries
3. When a capacitor's counter e.m.f. has risen to equal the battery voltage, the current is
   a. maximum in the circuit
   b. at 63.2% of its maximum Ohm's law value in the circuit
   c. zero in the circuit
   d. at 36.8% of its maximum Ohm's law value in the circuit
4. The total capacitance of two 100-microfarad capacitors connected in series is
   a. 25 microfarads
   b. 50 microfarads
   c. 100 microfarads
   d. 200 microfarads
5. When the magnetic field is collapsing, the induced e.m.f.
   a. aids and tends to prolong the impressed current
   b. opposes the impressed current
   c. has no effect upon the impressed current
   d. causes the impressed current to go immediately to zero
6. To increase the time required for the current to reach its maximum Ohm's law value in a series resistance and inductance circuit, it is necessary to
   a. increase the resistance
   b. decrease the resistance
   c. decrease the inductance
   d. increase the applied voltage
7. In a simple capacitor (fig. 9-6), the plate area is 2 square inches, the dielectric material is mica, and the distance between the plates is 0.01 inch. To increase the capacitance
   a. increase the distance between the plates
   b. change dielectric material from mica to paraffin paper
   c. decrease the plate area
   d. change dielectric material from mica to flint glass
8. What is the total capacitance of two 200-microfarad capacitors connected in series with each other and both in parallel with a 50-microfarad capacitor?
   a. 50 microfarads
   b. 250 microfarads
   c. 100 microfarads
   d. 150 microfarads
9. The unit of inductance is the
   a. ohm
   b. farad
   c. henry
   d. coulomb
10. The coefficient of coupling of two coils is
    a. increased by turning one coil axis at right angles to the other coil axis
    b. greatly increased with the addition of a soft iron core
    c. generally higher in an air core circuit than in an iron core circuit
    d. almost unity on a diamagnetic core
11. Factors that determine the capacitance of parallel-electrode capacitors are
    a. area of the plates and the type of dielectric
    b. thickness of the plates, type and thickness of the dielectric
    c. type and thickness of the dielectric and the plate area
    d. thickness of the dielectric, area of the plate, and the direction of the current flow
12. The time constant of a resistance-capacitance circuit is
    a. The time required to discharge a capacitor to 36.8% of its final voltage
    b. the time required to charge a capacitor to 36.8% of its maximum voltage
    c. equal to the circuit capacitance divided by the circuit resistance
    d. equal to the circuit resistance divided by the circuit capacitance
13. The voltage due to self-induction
    a. can only occur when the conductor is wound in the form of a coil
    b. is produced when the strength of the magnetic field changes
    c. is produced by moving a conductor through a magnetic field
    d. cannot occur in a direct-current circuit

14. If two coils are positioned with respect to each other so as to have unity coefficient of coupling and the inductance of coil A equals coil B, what is the mutual inductance between the two coils?
    a. Equal to the inductance of coil A.
    b. One half of the inductance of coil A.
    c. Double the inductance of coil A.
    d. Equal to the square root of the inductance of coil A.
15. The capacitance of a capacitor is inversely proportional to the
    a. frequency of the applied voltage
    b. dielectric constant
    c. active plate area
    d. distance between the plates
16. A 40-microfarad capacitor in series with 2,000 ohms is connected to a 200-volt source. The time constant is
    a. 0.05 second
    b. 0.08 second
    c. 0.50 second
    d. 0.80 second
17. To increase the inductance of a coil
    a. increase the permeability of the core material
    b. increase the length of the coil
    c. increase the magnitude of the current flow through the coil
    d. decrease the cross-sectional area of the coil

18. The charge that is stored in a capacitor depends upon
    a. voltage divided by the capacitance
    b. voltage multiplied by the capacitance
    c. capacitance divided by the voltage
    d. capacitance multiplied by the resistance

19. When selecting a capacitor for use in a circuit, its working voltage should be at least
    a. 10% greater than the highest voltage to be applied to it
    b. equal to the highest voltage to be applied to it
    c. 30% greater than the highest voltage to be applied to it
    d. 50% greater than the highest voltage to be applied to it

20. A battery, a switch, a resistor, and a coil are connected in series. What happens at the instant the switch is closed?
    a. The voltage across the resistor is maximum
    b. The voltage across the coil is maximum
    c. The current in the circuit is maximum
    d. The voltage across the resistor and the coil are minimum

21. Capacitance is the property of an electric circuit that
    a. opposes any change of current in the circuit
    b. opposes any change of voltage in the circuit
    c. is not affected by a change of voltage
    d. aids any change of current in the circuit

22. The time constant of an inductive-resistive circuit is
    a. that time required for a direct current to rise one-half of its maximum value
    b. a method of determining how much current would flow at the end of one second
    c. the product of the resistance and the inductance of a circuit
    d. the time in seconds required for the current to rise to 63.2% of its final Ohm's law value

23. When capacitors are connected in series, the resulting capacitance is found by
    a. a rule similar to that for combining parallel resistors
    b. a rule similar to that for combining resistors in series
    c. dividing the applied voltage by the total resistance of series circuit
    d. multiplying the applied voltage by the total resistance of series circuit

CHAPTER 10

INDUCTIVE AND CAPACITIVE REACTANCE

Inductive Reactance

FACTORS AFFECTING INDUCTIVE REACTANCE

In the preceding chapter, it was shown that when an alternating voltage is applied to an inductor, the inductor reacts in such a way as to oppose alternating-current flow. This opposition is thus referred to in general as an inductive reactance. The amount of opposition exhibited by a coil depends on the magnitude of its self-induced voltage, E_{ind}. The effective value of this self-induced voltage, or counter e.m.f. in volts, is

$$E_{ind} = 2\pi fLI,$$

where 2π is a constant, I is in effective amperes, L is in henrys, and f is in cycles per second. The induced voltage varies directly with the frequency, the inductance, and the current.

The amount of opposition to current flow offered by an inductor is referred to as its inductive reactance. This reactance is expressed as the ratio of the inductor's counter e.m.f. to the current through the inductor, or

$$X_L = \frac{E_{ind}}{I}$$

where X_L is the inductor's opposition to current flow measured in ohms, E_{ind} is the inductor's counter e.m.f. in volts, and I is the inductor current in amperes. Assuming the current and counter voltage have sine waveforms, the inductive reactance X_L, in ohms, is

$$X_L = 2\pi fL$$

Since the inductive reactance of a coil and its counter e.m.f. are closely related, anything which influences one must also influence the other. It has been shown that the counter e.m.f. of a coil depends on its inductance and the rate of flux change around the coil. Consequently, the inductive reactance must also be affected by the same influences. The rate of flux change per unit of time depends on the FREQUENCY of the inductor current. Flux must change more rapidly at high frequencies than at low frequencies. From the foregoing it can be seen that the inductive reactance of a coil depends primarily on (1) the coil's INDUCTANCE and (2) the FREQUENCY of the current flowing through the coil.

If frequency or inductance varies, inductive reactance must also vary. A coil's inductance does not vary appreciably after the coil is manufactured, unless it is designed as a variable inductor. Thus, frequency is generally the only variable factor affecting the inductive reactance of a coil. The coil's inductive reactance will vary directly with the applied frequency.

POWER IN AN INDUCTIVE CIRCUIT

The power in a d-c circuit is equal to the product of volts and amperes, but in an a-c circuit this is true only when the load is resistive, and has no reactance.

In a circuit possessing inductance only, the true power is zero (fig. 10-1). The current lags the applied voltage by 90°. The TRUE POWER is the average power actually consumed by the circuit, the average being taken over one complete cycle of alternating current. The APPARENT POWER is the product of r.m.s. volts and r.m.s. amperes. Thus, in figure 10-1 (A), the apparent power is 100 x 10 = 1,000 volt-amperes. However, the power absorbed by the coil during the time the current is rising (fig. 10-1 (B)), is returned to the source during the

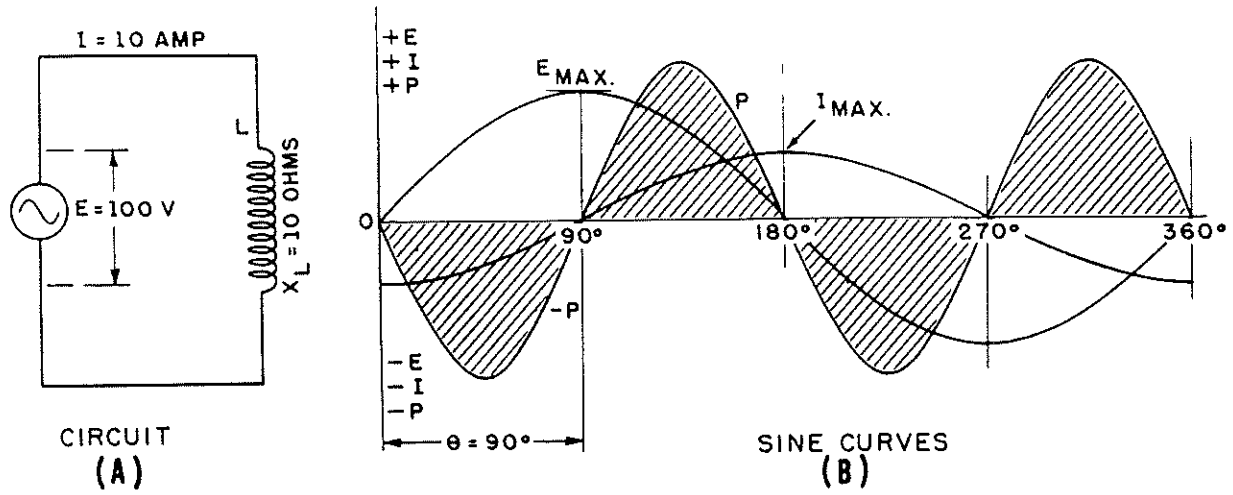


Figure 10-1.—Power in an inductive circuit.

time the current is falling, so that the average power is zero.

The product of instantaneous values of current and voltage yield the double frequency power curve *P*. (See fig. 10-1 (B).) The shaded areas under this curve above the *X* axis represent positive energy and the shaded areas below the *X* axis represent negative energy.

From 0 degrees to 90 degrees current is negative and falling; the magnetic field is collapsing and the energy in the field is being returned to the source (negative energy). The product of negative current and positive voltage is negative power.

From 90 degrees to 180 degrees the current is positive and rising; energy from the source is being stored in the rising magnetic field (positive energy). The product of positive current and positive voltage is equal to positive power.

From 180 degrees to 270 degrees current is positive and falling. Again energy is being returned to the source; the product of positive current and negative voltage is negative power.

From 270 degrees to 360 degrees current is negative and rising. Energy (positive) is being supplied by the source and stored in the magnetic field. The product of negative current and negative voltage is positive power.

Thus when current is rising, power is being supplied by the source and stored in the magnetic field; when current is falling, power is being returned to the source from the collapsing magnetic field. In the theoretically pure inductance shown in figure 10-1 the supplied power is equal to the returned power. Thus, average power used (true power) is zero.

The ratio of the true power to the apparent power in an a-c circuit is called the POWER FACTOR. It may be expressed as a percent or as a decimal. In the inductor of figure 10-1 (A), the power factor is $\frac{0}{1,000} = 0$. The power factor is also equal to the cos θ, where θ is the phase angle between the current and voltage. The phase angle between E and I in the inductor is $\theta = 90°$. Thus the power factor of an inductor of negligible losses is cos 90° = 0. The apparent power in a purely inductive circuit is called REACTIVE POWER and the unit of reactive power is called the VAR. This unit is derived from the first letters of the words volt-ampere-reactive.

RESISTANCE IN AN A-C CIRCUIT

In an a-c circuit containing only resistance, the current and voltage are always in phase ($\theta = 0°$). (See fig. 10-2.) The true power dissipated in heat in a resistor in an a-c circuit when sine waveforms of voltage and current are applied is equal to the product of the r.m.s. volts and the r.m.s. amperes. In the circuit of figure 10-2 (A) the power absorbed by the resistor is $P = EI = 100 \times 10 = 1,000$ watts. The product of the instantaneous values of current and voltage (fig. 10-2 (B)) gives the power curve, *P*, the axis of which is displaced above

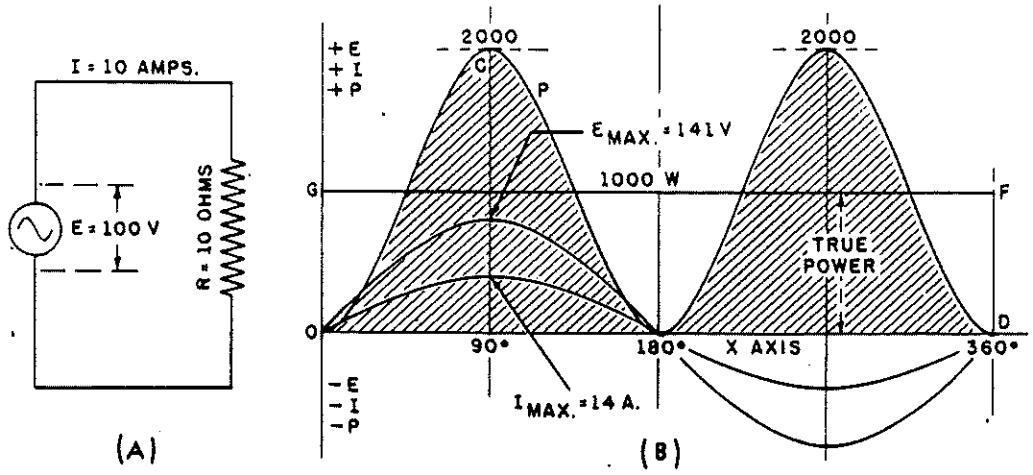


Figure 10-2.—Relation between E, I, and P in a resistive circuit.

the X axis by an amount that is proportional to 1,000 watts.

The true average power is

$$P = \frac{E_{max} \times I_{max}}{2} = E_{eff} \times I_{eff}.$$

The power factor of a resistive circuit is cos 0° = 1, or 100 percent. The apparent power in the resistor is also equal to the true power. The reactive power in the resistive circuit is zero.

RESISTANCE AND INDUCTIVE REACTANCE IN SERIES

Because any practical inductor must be wound with wire that has resistance, it is not possible to obtain a coil without some resistance. The resistance associated with a coil may be considered as a separate resistor, R, in the series with an inductor, L, which is purely inductive and contains only inductive reactance (fig. 10-3 (A)). The resistance has been exaggerated in this example to be of the same order of magnitude as the inductive reactance of the inductor in order to simplify the trigonometric solution.

If an alternating current, I_O, flows through the inductor a voltage drop occurs across both the resistor and the inductor. The voltage, E_γ, across the resistor is in phase with the current, and the voltage drop, E_L, across the inductor leads the current by 90° (fig. 10-3 (B)). The voltage across the resistor is assumed to be 50

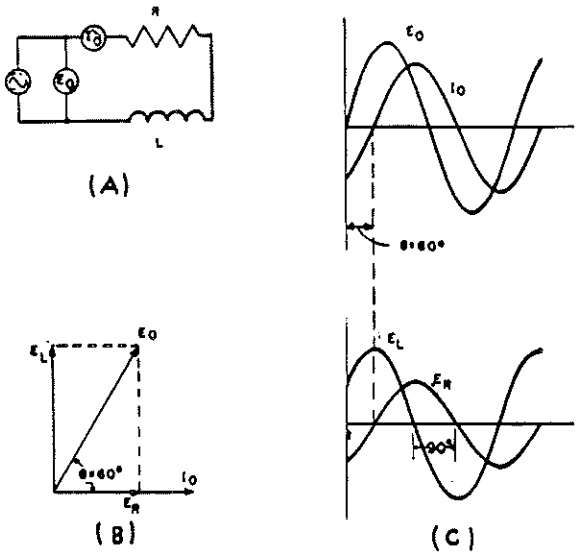


Figure 10-3.—Resistance and inductive reactance in series.

volts and the voltage across the inductor, 86.6 volts. These two voltages are 90° out of phase, as indicated in the figure. The applied voltage, E_O, is the hypotenuse of a right triangle, the sides of which are 50 and 86.6, respectively. Thus,

$$E_o = \sqrt{50^2 + 86.6^2} = 100 \text{ volts.}$$

The sine curves of circuit current, I_O, applied voltage, E_O, the voltage across the coil, E_L, and the voltage across the resistor, E_γ, are shown in figure 10-3 (C).

Impedance

Impedance is the total opposition to the flow of alternating current in a circuit that contains resistance and reactance. In the case of pure inductance, inductive reactance, X_L is the total opposition to the flow of current through it. In the case of pure resistance, R represents the total opposition. The combined opposition of R and X_L in series or in parallel to current flow is called IMPEDANCE. The symbol for impedance is Z.

The impedance of resistance in series with inductance is

$$Z = \sqrt{R^2 + X_L^2}$$

where Z, R, and X_L are the hypotenuse, base, and altitude respectively of a right triangle in which $\cos \theta = \frac{R}{Z}$, $\sin \theta = \frac{X_L}{Z}$, and $\tan \theta = \frac{X_L}{R}$. As mentioned before, $\cos \theta$ is equal to the circuit power factor; $\sin \theta$ is sometimes referred to as the reactive factor; and $\tan \theta$ is referred to as the quality, or Q, of a circuit or a circuit component. The trigonometric functions including the sine, cosine, and tangent of angles between 0° and 90° are given in appendix VI at the end of this training manual.

Power in a Series Circuit Containing R and X_L

The true power in any circuit is the product of the applied voltage, the circuit current, and the cosine of the phase angle between them. Thus, in figure 10-4, the true power is

$$P = EI \cos \theta = 100 \times 7.07 \ (\cos 45° = 0.707) = 500 \text{ watts.}$$

The power curve is partly above the X axis (fig. 10-4 (B)) and partly below it. The axis of the power curve is displaced above the X axis an amount proportional to the true power, $EI \cos \theta$. The apparent power in this circuit is

$$100 \times 7.07 = 707 \text{ volt-amperes.}$$

The power factor is

$$\cos \theta = \frac{\text{true power}}{\text{apparent power}} = \frac{500}{707} = 0.707, \text{ or } 70.7 \text{ percent.}$$

The reactive power in the L-R circuit is the product of $EI \sin \theta$ where $\sin \theta$ is the reactive factor. Thus the reactive power is

$$100 \times 7.07 \ (\sin 45° = 0.707) = 500 \text{ VARS (lagging).}$$

Summary of E, Z, and P Relations in L-R Circuit

The relation between voltage, impedance, and power in a series L-R circuit with sine waveforms applied is summarized in figure 10-5. In this example the circuit contains 12 ohms of resistance in series with 16 ohms of inductive reactance (fig. 10-5 (A)). The phase relations between the applied voltage; the voltage across the resistance, R; and the voltage across the inductance, L; are shown in figure 10-5 (B). The IR drop across R is 5 x 12 = 60 volts and forms the base of the right triangle. The altitude is the IX_L drop, or 5 x 16 = 80 volts, across L. The applied voltage represents the vector sum of the IR drop and the IX_L drop and is the hypotenuse of the right triangle. Its magnitude is 100 volts. All voltages are effective values.

The relation between resistance, inductive reactance, and impedance is shown by the vectors of figure 10-5 (C). The resistance of 12 ohms forms the base of the right triangle. The altitude of this triangle represents the inductive reactance of the coil and has a magnitude of 16 ohms. The combined impedance of the circuit is $Z = \sqrt{12^2 + 16^2} = 20$ ohms. In this triangle $\cos \theta = \frac{R}{Z}$. Thus $\cos \theta = \frac{12}{20} = 0.6$, from which $\theta = 53.1°$.

The relation between apparent power, true power, and reactive power is shown in figure 10-5 (D). The hypotenuse represents the apparent power and is equal to EI, or 100 x 5 = 500 volt-amperes. The base represents true power and is equal to $EI \cos \theta$, or 100 x 5 x 0.6 = 300 watts, where 0.6 = cos 53.1°. The altitude represents reactive power and is equal to $EI \sin \theta$, or 100 x 5 x 0.8 = 400 VARS, where 0.8 = sin 53.1°.

In all three vector diagrams the right triangles are similar. The common factor of current, I, makes their corresponding sides proportional. Thus the voltage triangle of figure 10-5 (B), is obtained by multiplying the corresponding sides of the impedance triangle of figure 10-5 (C), by I. The hypotenuse is equal to the applied voltage, or IZ = 5 x 20 = 100 volts. The base is equal to the voltage across R, or IR = 5 x 12 = 60. volts. The altitude is equal to

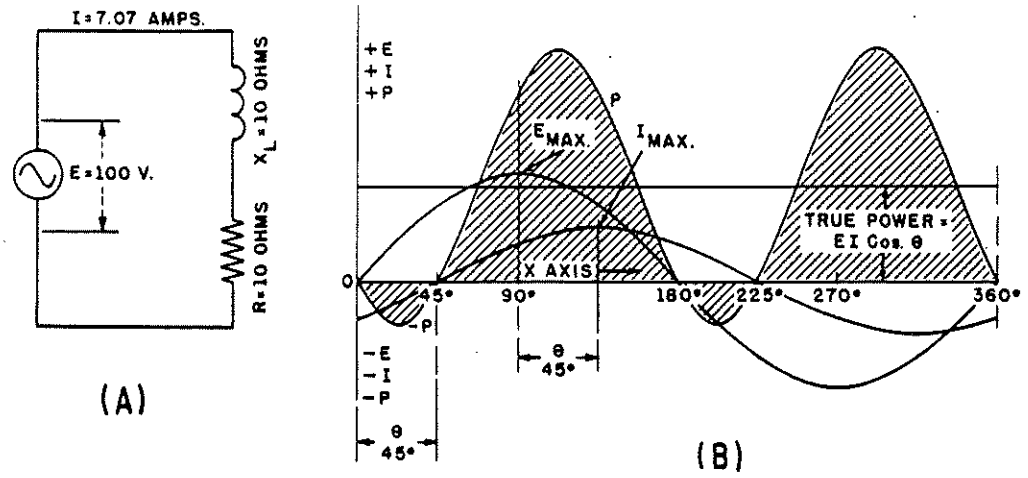


Figure 10-4.—Power in a circuit containing L and R in series.

the voltage across L, or IX_L = 5 x 16 = 80 volts.

Multiplying corresponding sides of the voltage triangle by I gives the power triangle of figure 10-5 (D). The hypotenuse is IZ times I, or I^2Z = 5^2 x 20 = 500 volt-amperes of apparent power. The base is IR times I, or I^2R = 5^2 x 12 = 300 watts of true power. The altitude is IX_L times I, or I^2X_L = 5^2 x 16 = 400 VARS of reactive power.

In the three vector diagrams, the circuit power factor is equal to the following ratios: In the voltage diagram,

$$\cos\theta = \frac{IR}{IZ} = \frac{60}{100} = 0.6.$$

In the impedance diagram,

$$\cos\theta = \frac{R}{Z} = \frac{12}{20} = 0.6.$$

In the power diagram,

$$\cos\theta = \frac{I^2R}{I^2Z} = \frac{300}{500} = 0.6.$$

In all three diagrams θ = 53.1° and the power factor is 60 percent.

Capacitive Reactance

Capacitance was defined in chapter 9 as that quality of a circuit that enables energy to be stored in an electric field. A capacitor is a device that possesses the quality of capacitance. In simple form it has been shown to consist of two parallel metal plates separated by an insulator, called a DIELECTRIC. The electric field consists of parallel lines of electric force which terminate in a positive charge on one plate and a negative charge on the other. The positive and negative charges on the plates establish the electric field in the dielectric because the dielectric prevents these charges from neutralizing each other.

CURRENT FLOW IN A CAPACITIVE CIRCUIT

A capacitor that is initially uncharged tends to draw a large current when a d-c voltage is first applied. During the charging period, the capacitor voltage rises. After the capacitor has received sufficient charge the capacitor voltage equals the applied voltage and the current flow ceases. If a sine-wave a-c voltage is applied to a pure capacitance the current is a maximum when the voltage begins to rise from zero, and the current is zero when the voltage across the capacitor is a maximum (fig. 10-6 (A)). The current leads the applied voltage by 90°, as indicated in the vector diagram of figure 10-6 (B).

ACTORS THAT CONTROL CHARGING CURRENT

Because a capacitor of large capacitance can store more energy than one of small capacitance, a larger current must flow to charge

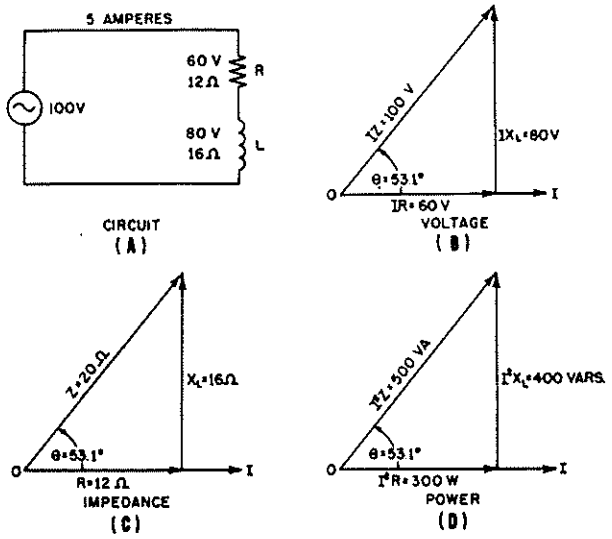


Figure 10-5.—Summary of relation between E, Z, and P in a series L-R circuit.

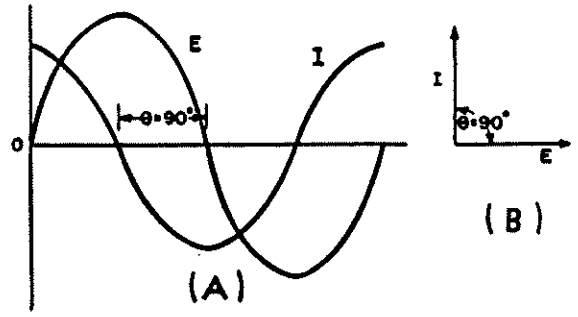


Figure 10-6.—Phase relation between E and I in a capacitive circuit.

a large capacitor than to charge a small one, assuming the same time interval in both cases. Also, because the current flow depends on the rate of charge and discharge, the higher the frequency, the greater is the current flow per unit time.

The charging current in a purely capacitive circuit varies directly with the capacitance, voltage, and frequency—

$$I = 2\pi fCE$$

where I is effective current in amperes, f is in cycles per second, C is the capacitance in farads, and E is in effective volts.

FORMULA FOR CAPACITIVE REACTANCE

The ratio of the effective voltage across the capacitor to the effective current is called the CAPACITIVE REACTANCE, X_C, and represents the opposition to current flow in a capacitive circuit of zero losses—

$$X_c = \frac{1}{2\pi fC}$$

When f is in cycles per second, and C is in farads, then X_C is in ohms.

Example: What is the capacitive reactance of a capacitor operating at a frequency of 60 cycles per second and having a capacitance of 133 microfarads, or 1.33×10^{-4} farads?

$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 60 \times 1.33 \times 10^{-4}} = 20 \text{ ohms.}$$

POWER IN A CAPACITIVE CIRCUIT

With no voltage or charge, the electrons in the dielectric between the capacitor plates rotate around their respective nuclei in normally circular orbits. When the capacitor receives a charge the positive plate repels the positive nuclei and at the same time the electrons in the dielectric are strained toward the positive plate and repelled away from the negative plate. This distorts the orbits of the electrons in the direction of the positive charge. During the time the electron orbits are changing from normal to the strained position there is a movement of electrons in the direction of the positive charge. This movement constitutes the DISPLACEMENT CURRENT in the dielectric. When the polarity of the plates reverses, the electron strain is reversed. If a sine-wave voltage is applied across the capacitor plates the electrons will oscillate back and forth in a direction parallel to the electrostatic lines of force. DISPLACEMENT CURRENT is a result of the movement of bound electrons, whereas CONDUCTION CURRENT represents the movement of free electrons.

Figure 10-7 (A) shows a capacitive circuit and figure 10-7 (B) indicates the sine waveform of charging current, applied voltage, and instantaneous power. The effective voltage is 70.7 volts. The effective current is 7.07 amperes. Because the losses are neglected, the phase angle between current and voltage is assumed to be 90°. The true power is zero, as indicated by the expression

$$P = EI \cos \theta$$
$$= 70.7 \times 7.07 \ (\cos 90° = 0) = 0 \text{ watt.}$$

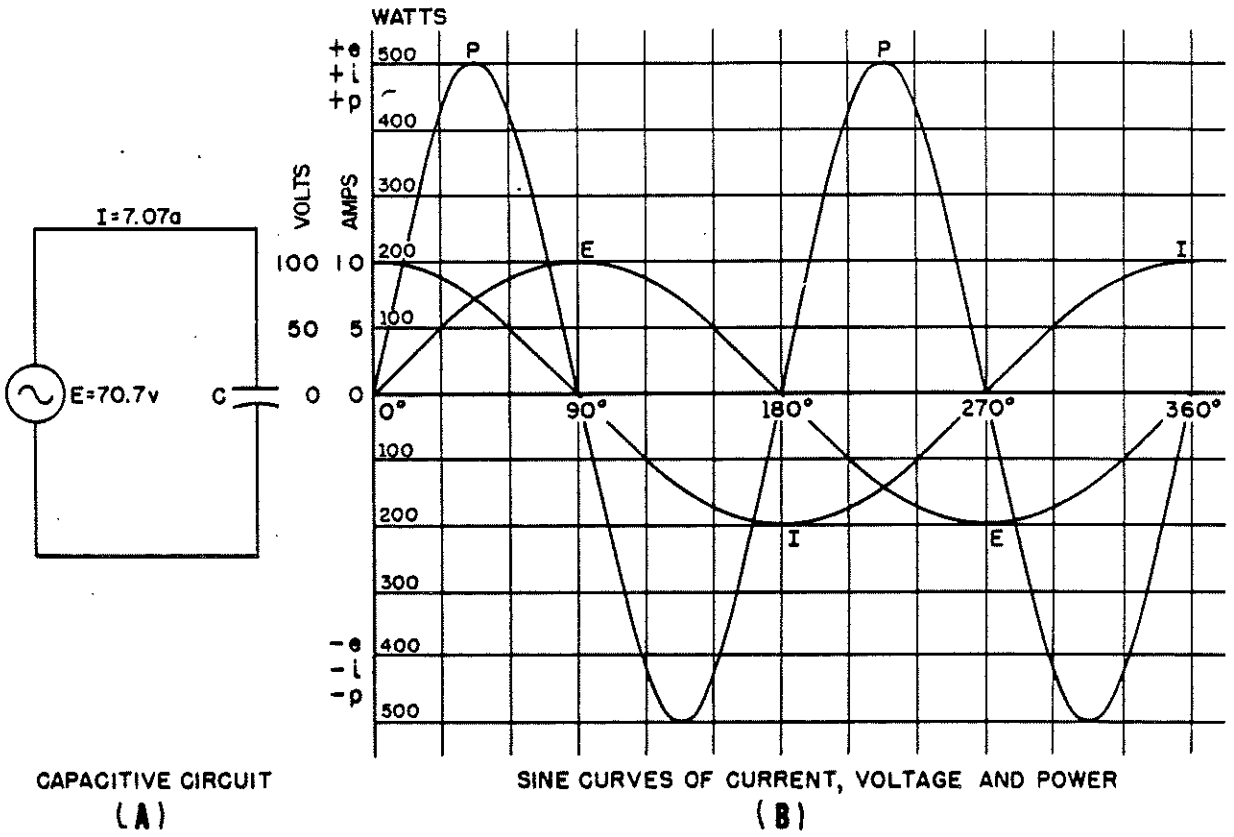


Figure 10-7.—Power in a capacitive circuit.

Multiplying instantaneous values of current and voltage over one cycle, or 360°, gives the power curve, *P*. During the first quarter cycle (from 0° to 90°) the applied voltage rises from zero to a maximum and the capacitor is receiving a charge. The power curve is positive during this period and represents energy stored in the capacitor. From 90° to 180° the applied voltage is falling from maximum to zero and the capacitor is discharging. The corresponding power curve is negative and represents energy returned to the circuit during this interval. The third quarter cycle represents a period of charging the capacitor and the fourth quarter cycle represents a discharge period. Thus, the average power absorbed by the capacitor is zero. The action is like the elasticity of a spring. Storing a charge in the capacitor is like compressing the spring. Discharging the capacitor is like releasing the pressure on the spring, thus allowing it to return the energy that was stored within it on compression.

The apparent power in the capacitor is EI = 70.7 x 7.07 = 500 volt-amperes. The reactive power in the capacitor is

$$EI \sin \theta = 70.7 \times 7.07 \times (\sin 90^\circ = 1) = 500 \text{ VARS (leading)}.$$

CAPACITIVE REACTANCE AND RESISTANCE IN SERIES

Losses that appear in capacitive circuits may be lumped in a resistor connected in series with the capacitor, as indicated in figure 10-8. In this example a 39.8-microfarad capacitor is connected in series with a 20-ohm resistor (fig. 10-8 (A)). The applied voltage across the *R-C* series circuit is 134 volts and the frequency is 100 cycles per second.

The capacitive reactance at this frequency is

$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 100 \times 39.8 \times 10^{-6}} = 40 \text{ ohms}.$$

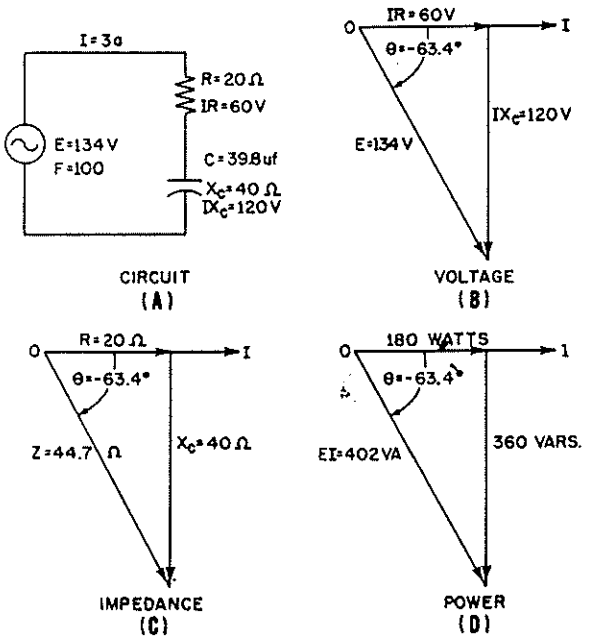


Figure 10-8.—Capacitive reactance and resistance in series.

Voltage Relation

The voltages across R and C are 90° out of phase and equal to 60 volts and 120 volts respectively, as shown in the vector diagram of figure 10-8 (B). The voltage across C is represented as IX_C and is plotted vertically downward from the horizontal in order to indicate that the current leads the voltage across the capacitor by 90°. Angle between the voltage across the capacitor and the circuit current is represented as -90° because it is measured clockwise from the horizontal reference vector, OI. The total voltage is equal to the vector sum of IR and IX_C and is represented in the figure as the hypotenuse of a right triangle the base of which represents the voltage across R, having an effective value of 60 volts and the voltage drop across C, having an effective value of 120 volts. The total (applied) voltage is 60V - 120V - 134 volts.

Impedance

The total impedance, Z, of the series circuit is

$$Z = \frac{E}{I} = \frac{134}{3} = 44.7 \text{ ohms.}$$

The impedance diagram is indicated in figure 10-8 (C). The base of the triangle represents the resistance, R, of the circuit and has a magnitude of 20 ohms. The capacitive reactance, X_C is represented as the altitude of the triangle and has a magnitude of 40 ohms. The total impedance may be represented as the hypotenuse of the triangle and has a magnitude of $\sqrt{20^2 + 40^2}$ = 44.7 ohms, which is also the ratio of the applied voltage to the circuit current. The impedance diagram is a right triangle that is similar to the triangle representing the voltage relation in figure 10-8 (B).

Power

The power relations are indicated in the vector diagram of figure 10-8 (D). This diagram is also a right triangle similar to the other two. The base represents the true power absorbed by the circuit resistance and has a magnitude of $I^2R = 3^2 \times 20 = 180$ watts. The altitude represents the reactive volt-ampere (leading) and has a magnitude of $I^2X_C = 3^2 \times 40 = 360$ VARS. The total apparent power is

$$EI = 134 \times 3 = 402 \text{ volt-amperes.}$$

Summary of E, Z, and P Relations in R-C Circuits

As mentioned previously, all three triangles are similar. The common factor is the circuit current; and the phase angle, θ, between E and I is equal to the same value in all three diagrams. Thus, the circuit power factor is equal to

$$\cos\theta = \frac{IR}{IZ} = \frac{60}{134} = 0.446 \text{ (fig. 10-8, B)}$$

$$\cos\theta = \frac{R}{Z} = \frac{20}{44.7} = 0.446 \text{ (fig. 10-9, C)}$$

$$\cos\theta = \frac{I^2R}{I^2Z} = \frac{180}{402} = 0.446 \text{ (fig. 10-8, D)}$$

and angle $\theta = 63.4°$ in all three triangles.

The true power is

$$EI \cos\theta = 134 \times 3 \times (\cos 63.4° = 0.446) = 180 \text{ watts.}$$

The reactive power is

$$EI \sin\theta = 134 \times 3 \times (\sin 63.4° = 0.894) = 360 \text{ VARS.}$$

The apparent power is

$$EI = 134 \times 3 = 402 \text{ volt-amperes.}$$

RESISTANCE, INDUCTANCE, AND CAPACITANCE IN SERIES

Relation of Voltages and Current in an R-L-C Series Circuit

When resistive, inductive, and capacitive elements are connected in series, their INDIVIDUAL characteristics are unchanged. That is, the current through and the voltage drop across the resistor are in phase while the voltage drops across the reactive components (assuming pure reactances) and the current through them are 90 degrees out of phase. However, a new relation must be recognized with the introduction of the three-element circuit. This pertains to the effect on total line voltage and current when connecting reactive elements in series, whose individual characteristics are opposite in nature, such as inductance and capacitance. Such a circuit is shown in figure 10-9

In the figure, note first that CURRENT is the common reference for all three element voltages, because there is only one current in a series circuit, and it is common to all elements. The common series current is represented by the dashed line in figure 10-9 (A). The voltage vector for each element, showing its individual relation to the common current, is drawn above each respective element. The total source voltage E is the vector sum of the individual voltages of IR, IX_L, and IX_C.

The three element voltages are arranged for summation in part (B). Since IX_L and IX_C are each 90° away from I, they are therefore 180° from each other. Vectors in direct opposition (180° out of phase) may be subtracted directly. The total reactive voltage E_X is the difference of IX_L and IX_C. Or, $E_X = IX_L - IX_C = 45 - 15 = 30$ volts. The final relationship of line voltage and current, as seen from the source, is shown in part (C). Had X_C been larger than X_L, the voltage would lag, rather than lead. When X_C and X_L are of equal values, line voltage and current will be in phase.

Impedance of R-L-C Series Circuits

The impedance of an R-L-C (three-element) series circuit is computed in exactly the same manner described for the two-element circuits in the preceding chapter. However, there is one additional operation to be performed. That is,

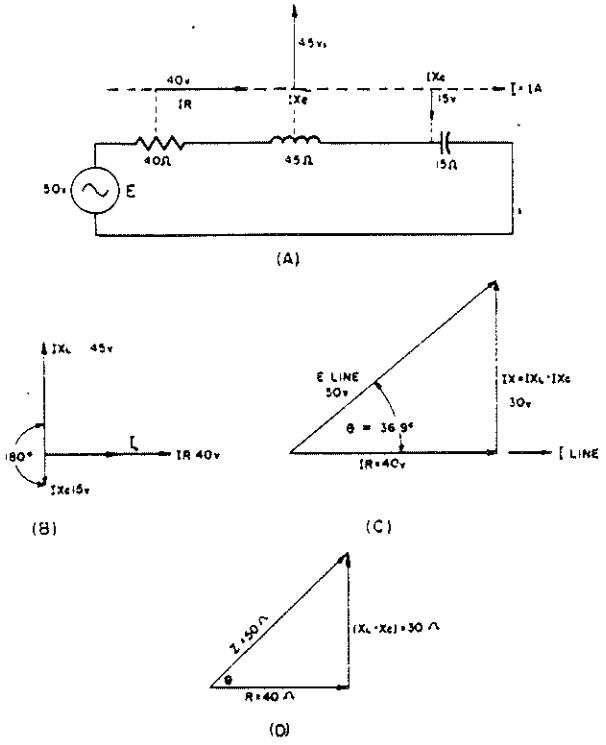


Figure 10-9.—Resistance, inductance, and capacitance connected in series.

the DIFFERENCE of X_L and X_C must be determined prior to computing total impedance. When employing the Pythagorean Theorem-based formula for determining series impedance, the net reactance of the circuit is represented by the quantity in parenthesis $(X_L - X_C)$. Applying this formula to the circuit in figure 10-9, the impedance is

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$= \sqrt{40^2 + (45 - 15)^2}$$

$$= \sqrt{1,600 + 900}$$

$$= \sqrt{2,500}$$

$$Z = 50\,\Omega.$$

Series impedance may also be determined by the use of vectorial layout, or triangulation. In an impedance triangle (fig. 10-9 (D)) for a series circuit, the base always represents the series resistance, the altitude represents the NET reactance $(X_L - X_C)$, and the hypotenuse represents total impedance.

It should be noted that as the DIFFERENCE of X_L and X_C becomes greater, total impedance also increases. Conversely, when X_L and X_C are equal, their effects cancel each other, and impedance is minimum, equal only to the series resistance. When X_L and X_C are equal, their INDIVIDUAL voltages are 90° out of phase with current, but their COLLECTIVE effect is zero, because they are equal and opposite in nature. Therefore, when X_L and X_C are equal, line voltage and current are in phase. This condition is the same as if there were only resistance and no reactances in the circuit. A circuit in this condition is said to be at RESONANCE.

Power in an R-L-C Series Circuit

Total true power in an R-L-C series circuit is the product of line voltage and current, times the cosine of the angle between them. When X_L and X_C are equal, total impedance is at a minimum, and thus current is maximum. When maximum current flows, the series resistor dissipates maximum power. When X_L and X_C are made unequal, total impedance increases, line current decreases, and moves out of phase with line voltage. Both the decrease in current and the creation of a phase difference cause a decrease in true power.

QUIZ

1. When frequency is increased in an inductive circuit, the current flow will
   a. increase because of greater inductive voltage
   b. increase because of less inductive voltage
   c. decrease because of greater inductive voltage
   d. decrease because of less inductive voltage

2. The unit of measurement for reactive power is the
   a. Volt Amp (VA)
   b. Volt Amp Wattage (VAW)
   c. Volt Amp Reactive (VAR)
   d. Volt Amp Kilo Watt (KVAW)

3. The prime factors that determine inductive reactance are
   a. frequency and current
   b. frequency and induced voltage
   c. inductance and frequency
   d. inductance and voltage

4. What are the prime factors affecting capacitive reactance?
   a. Frequency and capacitance
   b. Frequency and inductance
   c. Frequency and resistance
   d. Frequency squared

5. The reaction of an inductor to any change in current is known as inductive
   a. reactance
   b. voltage
   c. current
   d. resistance

6. What two quantities comprise the total power of an a-c circuit?
   a. Apparent power and VARS
   b. True power and VARS
   c. True power and VAWS
   d. True power and power factor

7. Power factor is the
   a. percentage of apparent power expended in heat
   b. amount of apparent power in an a-c circuit
   c. amount of apparent power plus true power
   d. efficiency of a circuit expressed as an angle

8. The unit of measurement for inductive reactance is the
   a. ohm
   b. volt
   c. ampere
   d. henry

9. What is the power factor of a pure capacitive circuit?
   a. 70.7%
   b. 86.6%
   c. 100%
   d. 0%

10. The self-induced voltage in a coil depends on the
   a. voltage applied
   b. inductive reactance
   c. c.e.m.f.
   d. current change in the coil

11. What is the path for current flow through a capacitor?
   a. Does not actually flow through
   b. From negative plate to positive plate
   c. From positive plate to negative plate
   d. From dielectric to plates

12. Power is described as the rate at which
   a. work is being done
   b. energy is being used
   c. energy is being expended
   d. all of the above are correct

13. What is the power characteristic of a pure inductive circuit?
   a. Positive power is the largest
   b. Positive and negative power are equal
   c. Negative power is the largest
   d. Negative power is the smallest

14. The vector sum of X_C and R in a series R-C circuit is the total
   a. opposition to voltage in the circuit
   b. capacitive reactance in the circuit
   c. resistance in the circuit
   d. opposition to current flow in the circuit

15. Self-induced voltage in an inductor will always oppose
   a. the applied voltage by 180 degrees
   b. circuit current
   c. the applied voltage by 90 degrees
   d. the circuit current by 180 degrees

16. What is the value of apparent current flow in a capacitive circuit when it is first energized?
   a. No current flow in a capacitive circuit
   b. Minimum
   c. Maximum
   d. Zero

17. What is the phase relationship between current and voltage in a resistive circuit?
   a. 90° phase difference
   b. 0° phase difference
   c. Out of phase
   d. Cannot be determined without numerical value of R

18. Voltage and current are considered to be out of phase with each other in a pure inductive circuit by what amount?
   a. Current leads voltage by 90 degrees
   b. Current lags voltage by 90 degrees
   c. Current leads voltage by 180 degrees
   d. Current lags voltage by 180 degrees

19. What is the phase relationship between current and voltage in a pure capacitive circuit?
   a. No phase angle
   b. Current lags voltage by 90 degrees
   c. Voltage leads current by 90 degrees
   d. Voltage lags current by 90 degrees

20. The phase angle between current and voltage in a circuit containing both resistive and inductive elements is
   a. greater than 0° but less than 90°
   b. a constant 45°
   c. 90° at all times
   d. 0° because X_L and R are equal

21. In the formula for capacitive reactance, the symbol "C" represents capacitance in
   a. farads
   b. micromicrofarads
   c. microfarads
   d. ohms

22. What is the effect on capacitor voltage when frequency is increased?
   a. Voltage increases
   b. Voltage decreases
   c. Voltage not affected
   d. Voltage is minimum

23. What is impedance?
   a. Opposition to current flow in an a-c circuit created by resistance and reactances
   b. Resistance of an a-c circuit
   c. Vector sum of voltage drops in an a-c circuit
   d. Current divided by voltage in an a-c circuit

CHAPTER 11

BASIC ELECTRICAL INDICATING INSTRUMENTS

In the field of electricity, as in all the other physical sciences, accurate quantitative measurements are essential. This involves two important items—numbers and units. Simple arithmetic is used in most cases, and the units are well-defined and easily understood. The standard units of current, voltage, and resistance as well as other units are defined by the National Bureau of Standards. At the factory, various instruments are calibrated by comparing them with established standards.

The technician commonly works with ammeters, voltmeters, ohmmeters, and electron-tube analyzers; but he may also have many occasions to use wattmeters, watt-hour meters, power-factor meters, synchroscopes, frequency meters, and capacitance-resistance-inductance bridges.

Electrical equipments are designed to operate at certain efficiency levels. To aid the technician in maintaining the equipment, technical instruction books and sheets containing optimum performance data, such as voltages and resistances, are prepared for all equipment.

To the technician, a good understanding of the functional design and operation of electrical instruments is important. In electrical service work one or more of the following methods are commonly used to determine if the circuits of an equipment are operating properly.

1. Use an ammeter to measure the amount of current flowing in a circuit.
2. Use a voltmeter to determine the voltage existing between two points in a circuit.
3. Use an ohmmeter or megger (megohmmeter) to measure circuit continuity and total or partial circuit resistance.

The technician may also find it necessary to employ a wattmeter to determine the total POWER being consumed by certain equipments. If he wishes to measure the ENERGY consumed by certain equipments or certain circuits, a watt-hour of kilowatt-hour meter is used.

For measuring other quantities such as power factor and frequency, which will be treated in a later chapter, the technician employs the appropriate instruments. In each case the instrument indicates the value of the quantity measured, and the technician interprets the information in a manner that will help him understand the way the circuit is operating. Occasionally the technician will need to determine the value of a capacitor or an inductor. Inductance or capacitance bridges may be employed for this purpose.

Although in this chapter the discussion is confined largely to d-c instruments, some of the instruments discussed may be used with alternating as well as direct current.

A thorough understanding of the construction, operation, and limitations of the basic types of electrical measuring instruments, coupled with the theory of circuit operation, is most essential in servicing and maintaining electrical equipment.

D'Arsonval Meter

CONSTRUCTION

The stationary permanent-magnet moving-coil meter is the basic movement used in most measuring instruments for servicing electrical, especially d-c, equipment. This type of movement is commonly called the D'Arsonval movement because it was first employed by the Frenchman D'Arsonval in making electrical measurements.

The basic D'Arsonval movement consists of a stationary permanent magnet and a movable

coil. When current flows through the coil the resulting magnetic field reacts with the magnetic field of the permanent magnet and causes the coil to rotate. The greater the amount of current flow through the coil the stronger the magnetic field produced and the stronger this field the greater the rotation of the coil. In order to determine the amount of current flow a means must be provided to indicate the amount of coil rotation. Either of two methods may be used—(1) the pointer arrangement, and (2) the light and mirror arrangement. In the pointer arrangement, one end of the pointer is fastened to the rotating coil and as the coil turns the pointer also turns. The other end of the pointer moves across a graduated scale and indicates the amount of current flow. A disadvantage of the pointer arrangement is that it introduces the problem of coil balance, especially if the pointer is long. An advantage of this arrangement is that it permits overall simplicity. The use of a mirror and a beam of light simplifies the problem of coil balance. When this arrangement is used to measure the turning of the coil, a small mirror is mounted on the supporting ribbon (fig. 11-1) and turns with the coil. An internal light source is directed to the mirror, and then reflected to the scale of the meter. As the moving coil turns, so does the mirror, causing the light reflection to move over the scale of the meter. The movement of the reflection is proportional to the movement of the coil, thus the amount of current being measured by the meter is indicated.

A simplified diagram of one type of stationary permanent-magnet moving-coil instrument is shown in figure 11-1. Such an instrument is commonly called a GALVANOMETER. The galvanometer indicates very small amounts (or the relative amounts) of current or voltage, and is distinguished from other instruments used for the same purpose in that the movable coil is suspended by means of metal ribbons instead of by means of a shaft and jewel bearings.

The movable coil of the galvanometer in figure 11-1 is suspended between the poles of the magnet by means of thin flat ribbons of phosphor bronze. These ribbons provide the conducting path for the current between the circuit under test and the movable coil. They also provide the restoring force for the coil. The restoring force, exerted by the twist in the ribbons, is the force against which the driving force of the coil's magnetic field (to be described later) is balanced in order to obtain a measurement of the current strength. The ribbons thus tend

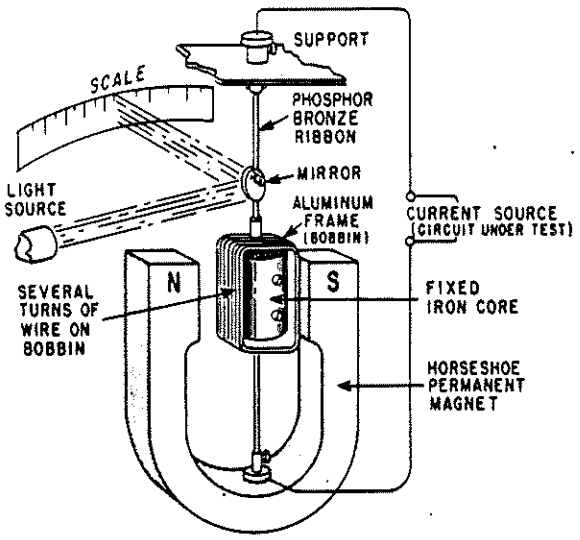


Figure 11-1.—Simplified diagram of a galvanometer.

to oppose the motion of the coil, and will twist through an angle that is proportional to the force applied to the coil by the action of the coil's magnetic field against the permanent field. The ribbons thus restrain or provide a counter force, for the magnetic force acting on the coil. When the driving force of the coil current is removed, the restoring force returns the coil to its zero position.

If a beam of light and mirrors are used, the beam of light is swept to the right or left across a central-zero translucent screen (scale) having uniform divisions. If a pointer is used, the pointer is moved in a horizontal plane to the right or left across a central-zero scale having uniform divisions. The direction in which the beam of light or the pointer moves depends on the direction of current through the coil.

This instrument is used to measure minute current as, for example, in bridge circuits. In modified form, the basic D'Arsonval movement has the highest sensitivity of any of the various types of meters in use today.

OPERATING PRINCIPLE

In order to understand the operating principle of the D'Arsonval meter it is first necessary to consider the force acting on a current-carrying conductor placed in a magnetic field. The magnitude of the force is proportional to the product of the magnitudes of the current and the field

strength. The field is established between the poles of a U-shaped permanent magnet and is concentrated through the conductor by means of a soft-iron stationary member mounted between the poles to complete the magnetic circuit. The conductor is made movable by shaping it in the form of a closed loop and mounting it between fixed pivots so that it is free to swing about the fixed iron member between the poles of the magnets. A convenient method of determining the direction of motion of the conductor is by the use of the RIGHT-HAND MOTOR RULE FOR ELECTRON FLOW (fig. 11-2).

To find the direction of motion of a conductor, the thumb, first finger, and second finger of the right hand are extended at right angles to each other, as shown. The first finger is pointed in the direction of the flux (toward the south pole) and the second finger is pointed in the direction of electron flow in the conductor. The thumb then points in the direction of motion of the conductor with respect to the field. The conductor, the field, and the force are mutually perpendicular to each other.

The force acting on a current-carrying conductor in a magnetic field is directly proportional to the field strength of the magnet, the active length of the conductor, and the intensity of the electron flow through it. Thus,

$$F = \frac{8.85 \times BLI}{10^8},$$

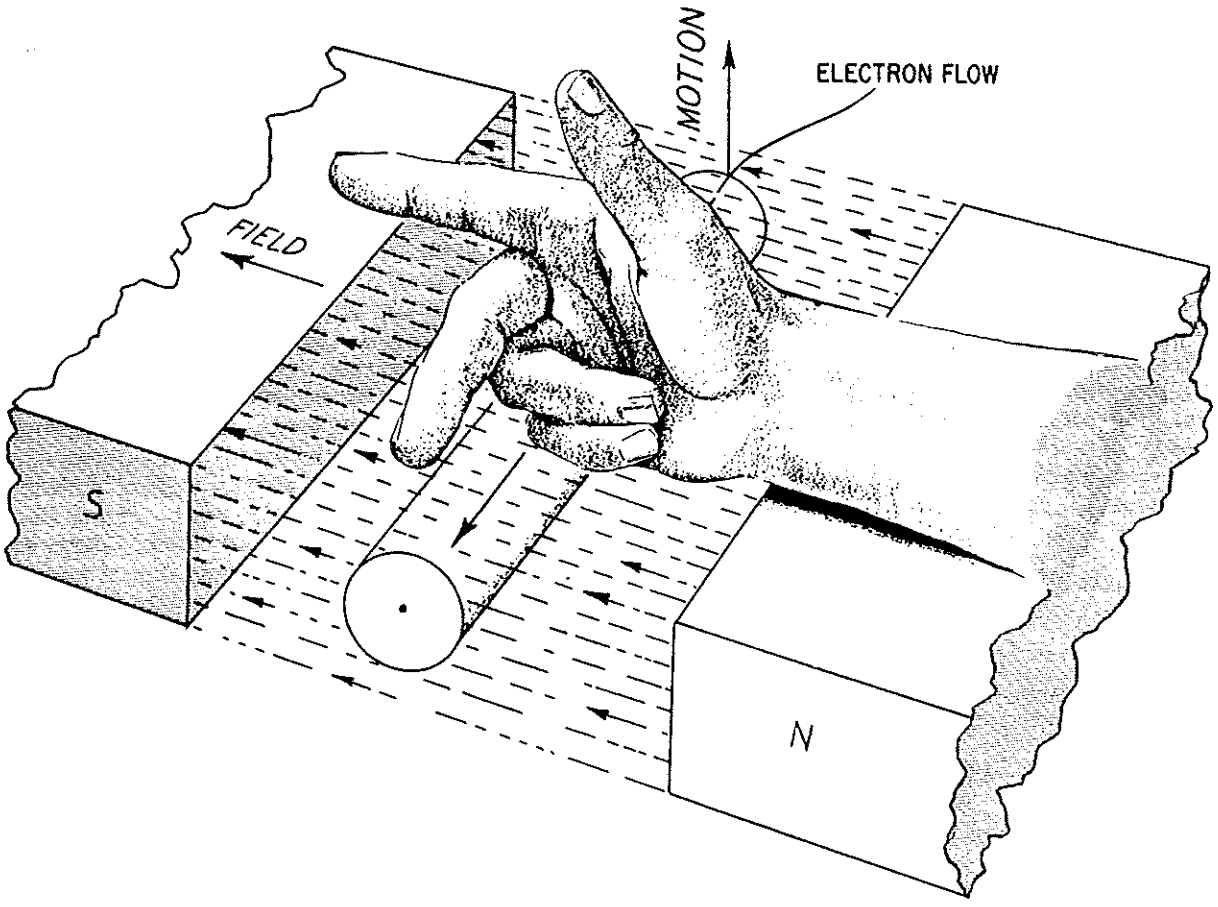


Figure 11-2.—Right-hand motor rule.

where F is the force in pounds, B the flux density in lines per square inch, L the active length of the conductor in inches, and I the current in amperes.

In the D'Arsonval-type meter, the length of the conductor is fixed and the strength of the field between the poles of the magnet is fixed. Therefore, any change in I causes a proportionate change in the force acting on the coil.

The principle of the D'Arsonval movement may be more clearly shown by the use of the simplified diagram (fig. 11-3) of the D'Arsonval movement commonly used in d-c instruments. In the diagram, only one turn of wire is shown; however, in an actual meter movement many turns of fine wire would be used, each turn adding more effective length to the coil. The coil is wound on an aluminum frame or bobbin, to which the pointer is attached. Oppositely wound hairsprings (one of which is shown in fig. 11-3), are also attached to the bobbin, one at either end. The circuit to the coil is completed through the hairsprings. In addition to serving as conductors, the hairsprings serve as the restoring force that returns the pointer to the zero position when no current flows.

As has been stated, the deflecting force is proportional to the current flowing in the coil. The deflecting force tends to rotate the coil against the restraining force of the hairspring. The angle of rotation is proportional to the force that the spring exerts against the moving coil (within the elastic limit of the spring). When the deflecting force and the restraining force are equal, the coil and the pointer cease to move. Because the restoring force is proportional to the angle of deflection, it follows that the driving force, and the current in the coil, are proportional to the angle of deflection. When current ceases to flow in the coil, the driving force ceases, and the restoring force of the springs returns the pointer to the zero position.

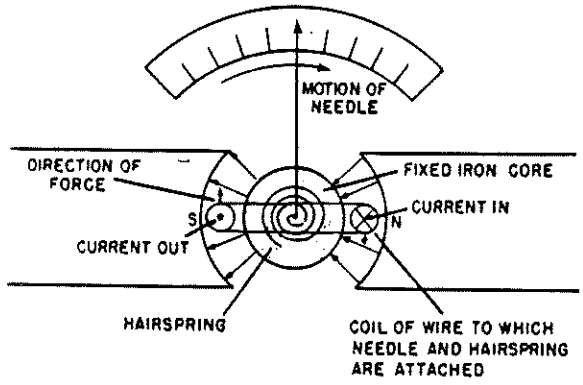


Figure 11-3.—D'Arsonval movement.

If the current through the single turn of wire is in the direction indicated (away from the observer on the right-hand side and toward the observer on the left-hand side), the direction of force, by the application of the right-hand motor rule, is upward on the left-hand side and downward on the right-hand side. The direction of motion of the coil and pointer is clockwise. If the current is reversed in the wire, the direction of motion of the coil and pointer is reversed.

A detailed view of the basic D'Arsonval movement, as commonly employed in ammeters and voltmeters, is shown in figure 11-4. This instrument is essentially a MICROAMMETER because the current necessary to activate it is of the order of 1 microampere. The principle of operation is the same as that of the simplified versions discussed previously. The iron core is rigidly supported between the pole pieces and serves to concentrate the flux in the narrow space between the iron core and the pole piece—in other words, in the space through which the coil and the bobbin moves. Current flows into one hairspring, through the coil, and out of the other hairspring. The restoring force of the spiral springs returns the pointer to the normal, or zero, position when the current through the coil is interrupted. Conductors connect the hairsprings with the outside terminals of the meter.

If the instrument is not damped—that is, if viscous friction or some other type of loss is not introduced to absorb the energy of the moving element—the pointer will oscillate for a long time about its final position before coming to rest. This action makes it nearly impossible to obtain a reading and some form of damping is necessary to make the meter practicable. Damping is accomplished in many D'Arsonval movements by means of the motion of the aluminum bobbin upon which the coil is wound. As the bobbin oscillates in the magnetic field, an e.m.f. is induced in it because it cuts through the lines of force. Therefore, according to Lenz's law, induced currents flow in the bobbin in such a direction as to oppose the motion, and the bobbin quickly comes to rest in the final position after going beyond it only once.

In addition to factors such as increasing the flux density in the air gap, the overall sensitivity of the meter can be increased by the use of a lightweight rotating assembly (bobbin, coil, and

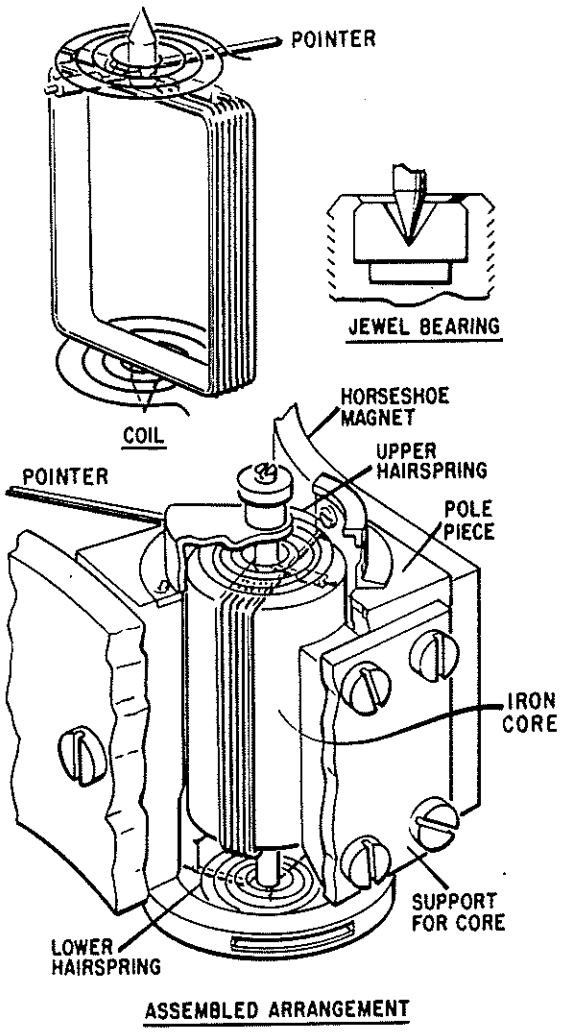


Figure 11-4.—Detailed view of basic D'Arsonval movement.

pointer) and by the use of jewel bearings as shown.

While D'Arsonval-type galvanometers are useful in the laboratory for measurements of extremely small currents, they are not portable, compact or rugged enough for use in the maintenance of military equipment. The Weston meter movement is used instead.

The Weston meter uses the principles of the D'Arsonval galvanometer, but it is portable, compact, rugged and easy to read. In the Weston meter the coil is mounted on a shaft fitted between two permanently mounted jewel bearings. A lightweight pointer is attached to and turns with the coil; the pointer indicates the amount of current flow. Figure 11-5 (A) illustrates this movement.

Balance springs on each end of the shaft exert opposite turning forces on the coil. By adjusting the tension of one spring, the meter pointer may be adjusted to read zero on the meter scale. Since temperature change affects both coil springs equally, this factor can be discounted. As the meter coil turns, one spring tightens to provide a restoring force; at the same time the other spring releases its tension. In addition to providing tension, the springs are also used as conductors to carry current from the meter terminals to the moving coil.

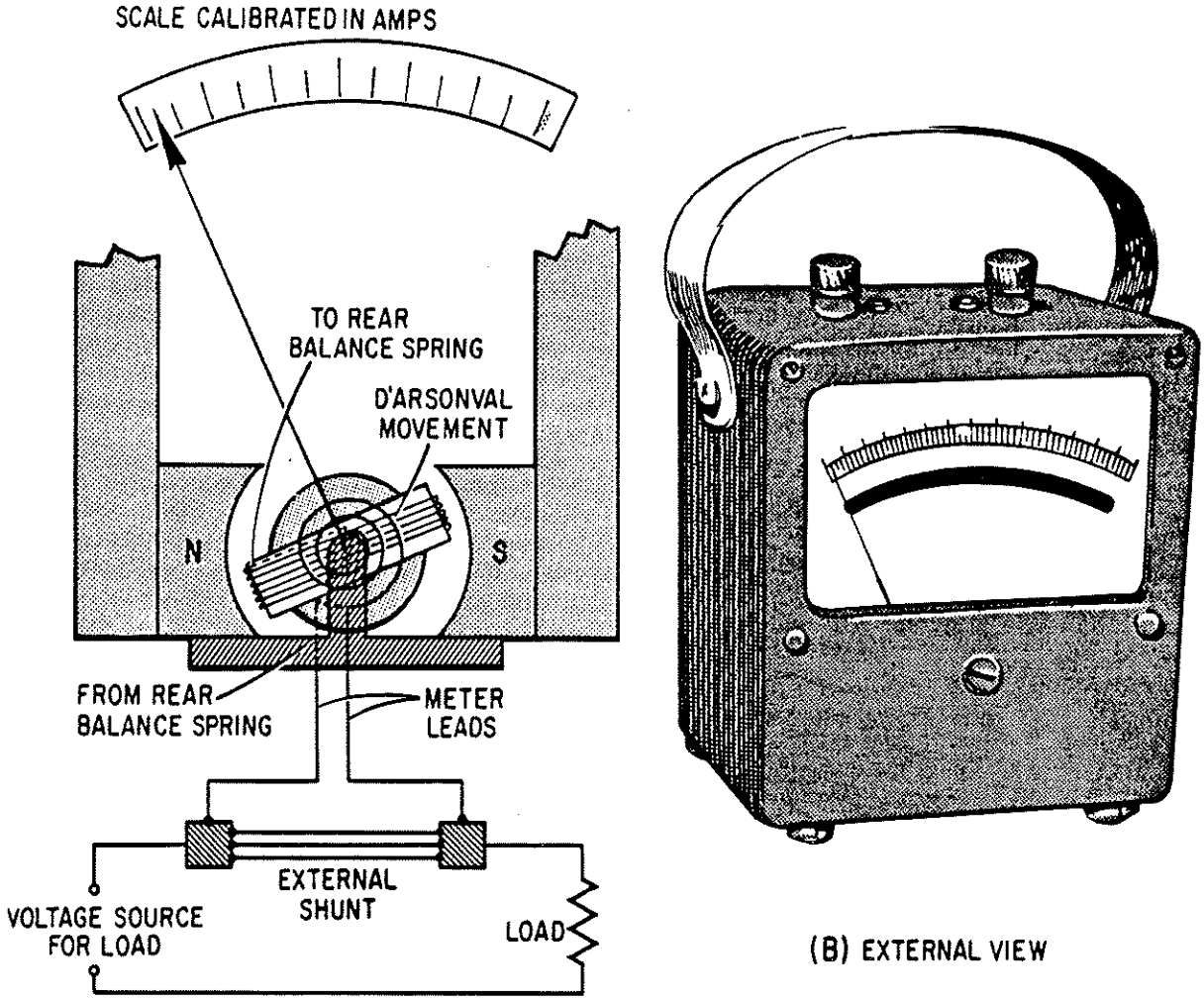
In order that the turning force will increase uniformly as the current increases, the horseshoe magnet poles are shaped to form semicircles. The amount of current required to turn the meter pointer to full-scale deflection depends upon the magnet's strength and the number of turns of wire in the moving coil. This amount of current is the ammeter's MAXIMUM ALLOWABLE AMOUNT. A further increase of meter current would damage the meter.

Ammeter

CONSTRUCTION

The small size of the wire with which an ammeter's movable coil is wound places severe limits on the current that may be passed through the coil. Consequently, the basic D'Arsonval movement discussed thus far may be used to indicate or measure only very small currents—for example, microamperes (10^{-6} amperes) or milliamperes (10^{-3} amperes), depending on meter sensitivity.

To measure a larger current, a shunt must be used with the meter. A shunt is a heavy low-resistance conductor connected across the meter terminals to carry most of the load current. This shunt has the correct amount of resistance to cause only a small part of the total circuit current to flow through the meter coil. The meter current is proportional to the load current. If the shunt is of such a value that the meter is calibrated in milliamperes, the instrument is called a MILLIAMMETER. If the shunt is of such



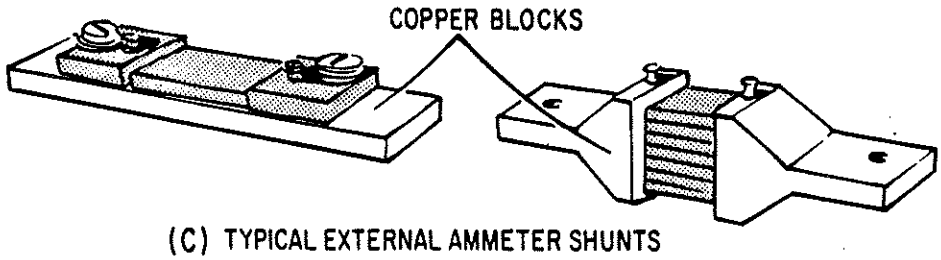


Figure 11-5.—Weston ammeter employing D'Arsonval principle in its movement.

a value that the meter is calibrated in amperes, it is called an AMMETER.

A single type of standard meter movement is generally used in all ammeters, no matter what the range of a particular meter. For example, meters with working ranges of zero to 10 amperes, zero to 5 amperes, or zero to 1 ampere all use the same galvanometer movement. The designer of the ammeter simply calculates the correct shunt resistance required to extend the range of the one-milliampere meter movement to measure any desired amount of current. This shunt is then connected across the meter terminals. Shunts may be located inside the meter case (internal shunt) or somewhere away from the meter (external shunt), with leads going to the meter. An external shunt arrangement is shown in figure 11-5 (A). Some typical external shunts are shown in part (C).

The shunt strips are usually made of manganin; an alloy having an almost zero temperature coefficient of resistance. The ends of the shunt strips are embedded in heavy copper blocks to which are attached the meter coil leads and the line terminals. To insure accurate readings, the meter leads for a particular ammeter should not be used interchangeably with those for a meter of a different range. Slight changes in lead length and size may vary the resistance of the meter circuit and thus its current, and may cause an incorrect meter reading. External shunts are generally used where currents greater than 50 amperes must be measured.

It is important to select a suitable shunt when using an external shunt ammeter so that the scale indication is easily read. For example, if the scale has 150 divisions and the load current to be measured is known to be between 50 and 100 amperes, a 150-ampere shunt is suitable. If the scale deflection is 75 divisions, the load current is 75 amperes, the needle will deflect half-scale when using the same 150-ampere shunt.

A shunt having exactly the same current rating as the estimated normal load current should never be selected because any abnormally high load would drive the pointer off scale and might damage the movement. A good choice would bring the needle somewhere near the mid-scale indication, when the load is normal.

EXTENDING THE RANGE BY USE OF INTERNAL SHUNTS

For limited current ranges (below 50 amperes), internal shunts are most often employed. In this manner the range of the meter may be easily changed by selecting the correct internal shunt having the necessary current rating. Before the required resistance of the shunt for each range can be calculated, the resistance of the meter movement must be known.

For example, suppose it is desired to use a 100-microampere D'Arsonval meter having a resistance of 100 ohms to measure line currents up to 1 ampere. The meter deflects full scale when the current through the 100-ohm coil is 100 microamperes. Therefore, the voltage drop across the meter coil is IR, or

$$0.0001 \times 100 = 0.01 \text{ volt.}$$

Because the shunt and coil are in parallel, the shunt must also have a voltage drop of 0.01 volt. The current that flows through the shunt is the difference between the full-scale meter current and the line current. In this case, the meter current is 100×10^{-6}, or 0.0001 ampere. This current is negligible compared with the line (shunt) current, so the shunt current is approximately 1 ampere. The resistance, R_S, of the shunt is therefore

$$R_s = \frac{E}{I} = \frac{0.01}{1} = 0.01 \text{ ohm (approx.)},$$

and the range of the 100-microampere meter has been increased to 1 ampere by paralleling it with the 0.01-ohm shunt.

The 100-microampere instrument may also be converted to a 10-ampere meter by the use of a proper shunt. For full-scale deflection of the meter the voltage drop, E, across the shunt (and across the meter) is still 0.01 volt. The meter current is again considered negligible, and the shunt current is now approximately 10 amperes. The resistance, R_S, of the shunt is therefore

$$R_s = \frac{E}{I} = \frac{0.01}{10} = 0.01 \text{ ohm.}$$

The same instrument may likewise be converted to a 50-ampere meter by the use of the

proper type of shunt. The current, I_S, through the shunt is approximately 50 amperes and the resistance, R_S, of the shunt is

$$R_s = \frac{E}{I_s} = \frac{0.01}{50} = 0.0002 \text{ ohm.}$$

Various values of shunt resistance may be used, by means of a suitable switching arrangement, to increase the number of current ranges that may be covered by the meter. Two switching arrangements are shown in figure 11-6. Figure 11-6 (A), is the simpler of the two arrangements from the point of view of calculating the value of the shunt resistors when a number of shunts are used. However, it has two disadvantages:

1. When the switch is moved from one shunt resistor to another the shunt is momentarily removed from the meter and the line current then flows through the meter coil. Even a momentary surge of current could easily damage the coil.

2. The contact resistance—that is, the resistance between the blades of the switch when they are in contact—is in series with the shunt but not with the meter coil. In shunts that must pass high currents the contact resistance becomes an appreciable part of the total shunt resistance. Because the contact resistance is of a variable nature, the ammeter indication may not be accurate.

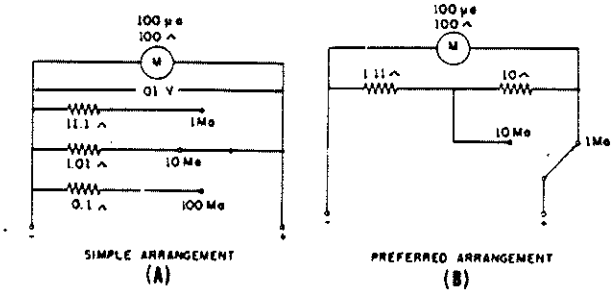


Figure 11-6.—Ways of connecting internal shunts.

A more generally accepted method of range switching is shown in figure 11-6 (B). Although only two ranges are shown, as many ranges as needed can be used. In this type of circuit the range selector switch contact resistance is external to the shunt and meter in each range position, and therefore has no effect on the accuracy of the current measurement.

CURRENT-MEASURING INSTRUMENTS MUST ALWAYS BE CONNECTED IN SERIES WITH A CIRCUIT AND NEVER IN PARALLEL WITH IT. If an ammeter were connected across a constant-potential cource of appreciable voltage the shunt would become a short circuit, and the meter would burn out.

If the approximate value of current in a circuit is not known, it is best to start with the highest range of the ammeter and switch to progressively lower ranges until a suitable reading is obtained.

Most ammeter needles indicate the magnitude of the current by being deflected from left to right. If the meter is connected with reversed polarity, the needle will be deflected backwards, and this action may damage the movement. Hence the proper polarity should be observed in connecting the meter in the circuit. That is, the meter should always be connected so that the electron flow will be into the negative terminal and out of the positive terminal.

Figure 11-7 shows various circuit arrangements; the ammeter or ammeters are properly connected for measuring current in various portions of the circuits.

Voltmeter

CONSTRUCTION

The 100-microampere D'Arsonval meter used as the basic meter for the ammeter may also be used to measure voltage if a high resistance is placed in series with the moving coil of the meter. For low-range instruments, this resistance is mounted inside the case with the D'Arsonval movement and typically consists of resistance wire having a low temperature coefficient and wound either on spools or card frames. For higher voltage ranges, the series resistance may be connected externally. When this is done the unit containing the resistance is commonly called a MULTIPLIER.

A simplified diagram of a voltmeter is shown in figure 11-8 (A). The resistance coils are treated in such a way that a minimum amount of moisture will be absorbed by the insulation. Moisture reduces the insulation resistance and increases leakage currents, which cause incorrect readings. Leakage currents through the insulation increase with length of resistance wire and become a factor that limits the magnitude

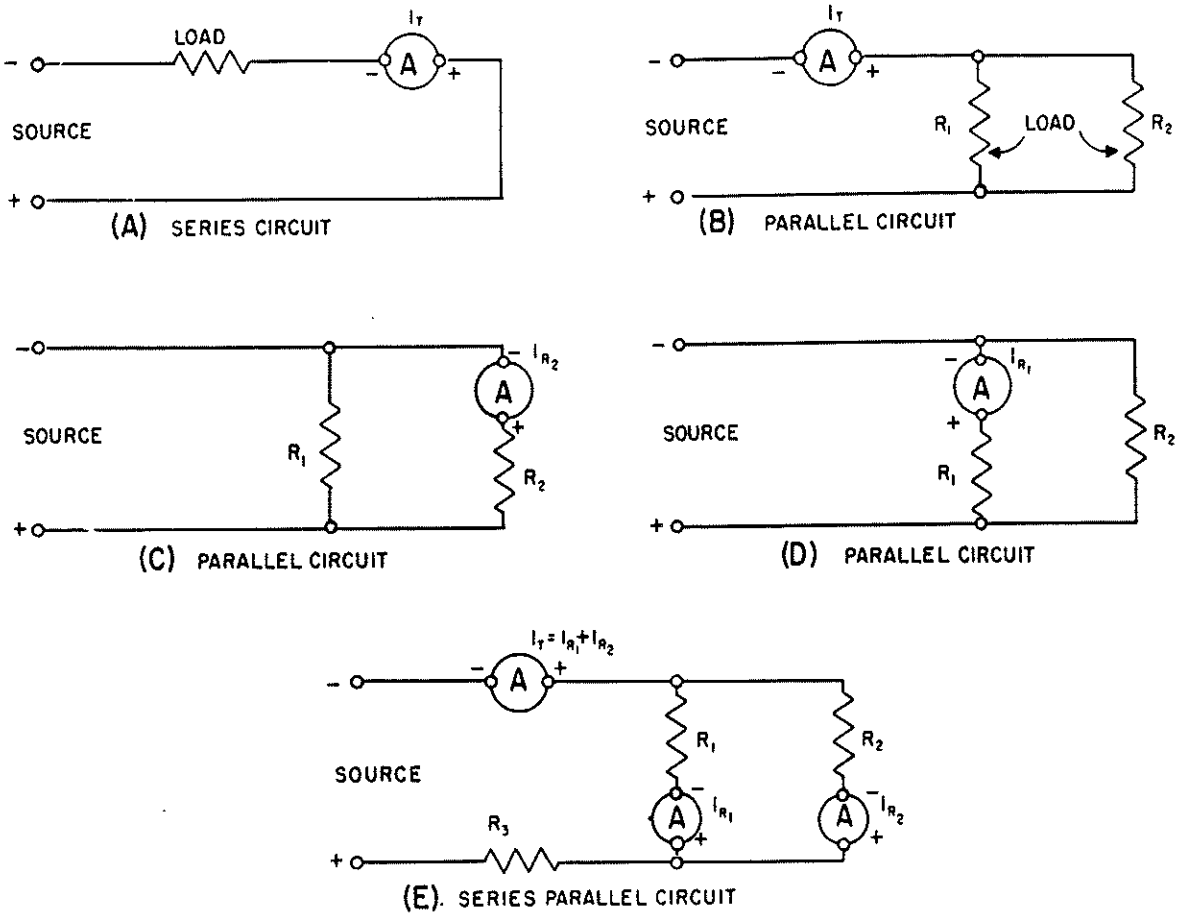


Figure 11-7.—Proper ammeter connections.

of voltage that may be measured. An external view of a voltmeter is shown in figure 12-8 (B).

EXTENDING THE RANGE

The value of the necessary series resistance is determined by the current required for full-scale deflection of the meter and by the range of voltage to be measured. Because the current through the meter circuit is directly proportional to the applied voltage, the meter scale can be calibrated directly in volts for a fixed series resistance.

For example, assume that the basic meter (microammeter) is to be made into a voltmeter with a full-scale reading of 1 volt. The coil resistance of the basic meter is 100 ohms, and 0.0001 ampere (100 microamperes) causes a full-scale deflection. The total resistance, R, of the meter coil and the series resistance is

$$R = \frac{E}{I} = \frac{1}{0.0001} = 10{,}000 \text{ ohms},$$

and the series resistance alone is

$$R_s = 10{,}000 - 100 = 9{,}900 \text{ ohms}.$$

Multirange voltmeters utilize one meter movement with the required resistances connected in series with the meter by a convenient switching arrangement. A multirange voltmeter with three ranges is shown in figure 11-9. The total circuit resistance for each of the three ranges beginning with the 1-volt range is:

$$R = \frac{E}{I} = \frac{1}{100} = 0.01 \text{ megohm},$$

$$= \frac{100}{100} = 1 \text{ megohm},$$

$$= \frac{1{,}000}{100} = 10 \text{ megohms}.$$

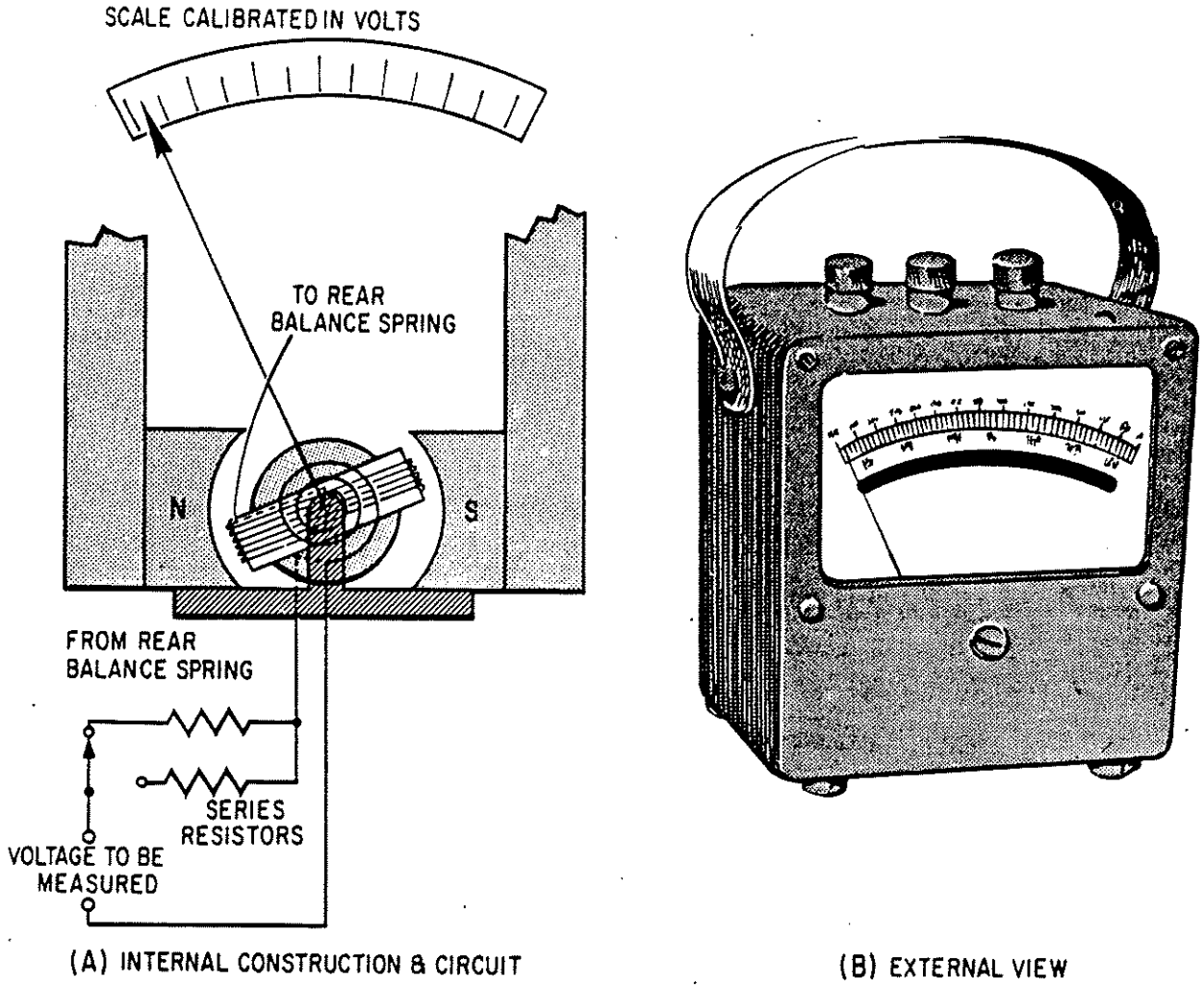


Figure 11-8.—Simplified voltmeter circuit.

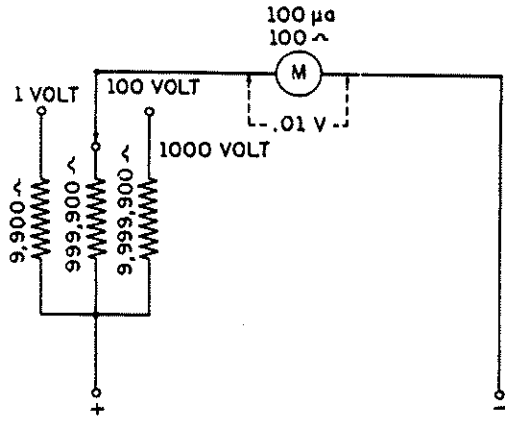


Figure 11-9.—Multirange voltmeter.

VOLTAGE-MEASURING INSTRUMENTS ARE CONNECTED ACROSS (IN PARALLEL WITH) A CIRCUIT. If the approximate value of the voltage to be measured is not known, it is best to start with the highest range of the voltmeter and progressively lower the range until a suitable reading is obtained.

In many cases, the voltmeter is not a central-zero indicating instrument. Thus, it is necessary to observe the proper polarity when connecting the instrument to the circuit, as is the case in connecting the d-c ammeter. The positive terminal of the voltmeter is always connected to the positive terminal of the source, and the negative terminal to the negative terminal of the source when the source voltage is being measured. In

any case, the voltmeter is connected so that electrons will flow into the negative terminal and out of the positive terminal of the meter.

INFLUENCE IN A CIRCUIT

The function of a voltmeter is to indicate the potential difference between two points in a circuit. When the voltmeter is connected across a circuit, it shunts the circuit. If the voltmeter has low resistance it will draw an appreciable amount of current. The effective resistance of the circuit will be lowered and the voltage reading will consequently be lowered.

When voltage measurements are made in high-resistance circuits, it is necessary to use a high-resistance voltmeter to prevent the shunting action of the meter. The effect is less noticeable in low-resistance circuits because the shunting effect is less.

SENSITIVITY

The sensitivity of a voltmeter is given in ohms per volt, (Ω/E), and may be determined by dividing the resistance R_m, of the meter plus the series resistance, R_S, by the full-scale reading in volts. Thus,

$$\text{sensitivity} = \frac{R_m + R_s}{E}$$

This is the same as saying that the sensitivity is equal to the reciprocal of the current (in amperes)—that is,

$$\text{sensitivity} = \frac{\text{ohms}}{\text{volts}} = \frac{1}{\frac{\text{volts}}{\text{ohms}}} = \frac{1}{\text{amperes}}.$$

Thus, the sensitivity of a 100-microampere movement is the reciprocal of 0.0001 ampere, or 10,000 ohms per volt.

Table 11-1 shows how the sensitivity of permanent-magnet movable-coil voltmeters has been increased over many years of manufacture. The table indicates the sensitivity of a 0 to 150-volt voltmeter, its resistance, and the current required to produce a full-scale deflection.

Table 12-1.—Increase in sensitivity in voltmeters.

Time of manufacture	Sensitivity	Resistance	Current to deflect full scale
Before 1924.	10 ohms per volt	1.5 k-ohms	100 ma.
After 1924.	100 ohms per volt	15 k-ohms	10 ma.
Today.	1,000 ohms per volt	150 k-ohms	1 ma.
	20,000 ohms per volt	3 megohms	50 μa.
	200,000 ohms per volt	30 megohms	5 μa.

ACCURACY

The accuracy of a meter is generally expressed in percent. For example, a meter that has an accuracy of 1 percent will indicate a value that is within 1 percent of the correct value. The statement means that if the correct value is 100 units, the meter indication may be anywhere within the range of 99 to 101 units.

The sensitivity has been increased by increasing the strength of the permanent magnet, by using lighter weight materials for the moving element (consistent with increased number of turns on the coil), and by using sapphire jewel bearings to support the moving coil.

Electrodynamometer-Type Meter

The electrodynamometer-type meter differs from the galvanometer-type meter in that no permanent magnet is used. Instead, two fixed coils are utilized to produce the magnetic field. Two movable coils are also used in this type meter.

The two fixed coils are connected in series and positioned coaxially, with a space between them. The two movable coils are also positioned coaxially, and are connected in series. The two pairs of coils (fixed pair and movable pair) are further connected in series with each other. The movable-coil unit is pivot-mounted between the fixed coils.

This meter arrangement is illustrated in figure 11-10.

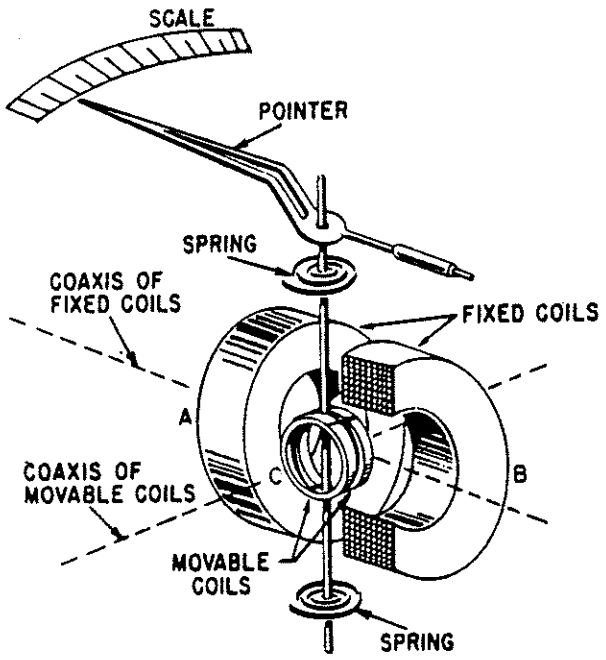


Figure 11-10.—Inside construction of an electrodynamometer.

The central shaft on which the movable coils are mounted is restrained by spiral springs which hold the pointer at zero when no current is flowing through the coil. These springs also serve as conductors for delivering current to the movable coils. Since these conducting springs are very small, the meter cannot carry a very heavy current.

When used as a voltmeter, no difficulty in construction is encountered, because the current required is not more than 0.1 ampere. This amount of current can be brought in and out of the moving coil through the springs. When the electrodynamometer is used as a voltmeter, its internal connections and construction are as shown in figure 11-11 (A). The fixed coils *a* and *b* are wound with fine wire, since the current through them will be no more than 0.1 ampere. They are connected directly in series with the movable coil *c* and the series current-limiter resistance. For ammeter applications, however, a special type construction must be used, because the large currents that flow through the meter cannot be carried through the moving coils.

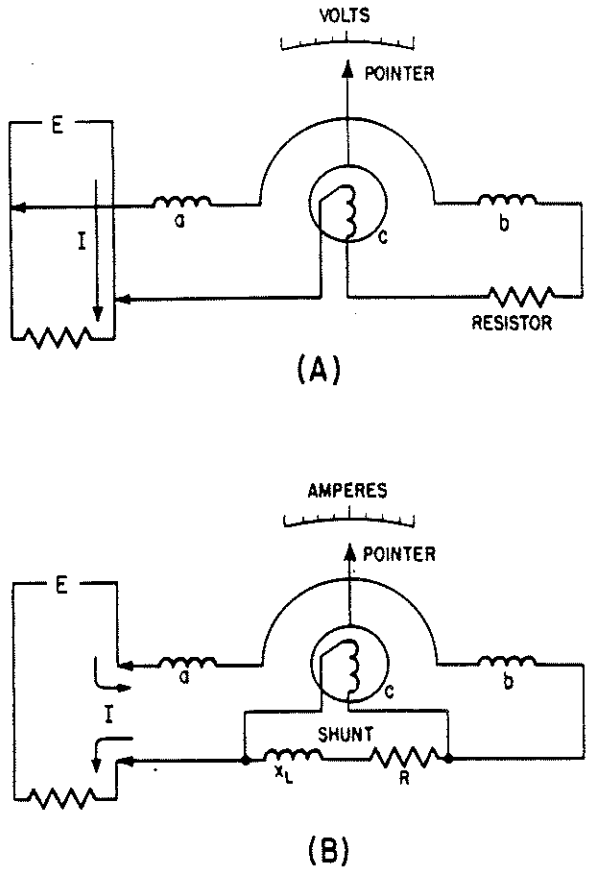


Figure 11-11.—Circuit arrangement of electrodynamometer type meter, (A) voltmeter, (B) ammeter.

In the ammeter, the stationary coils *a* and *b* of figure 11-11 (B), are generally wound of heavier wire, to carry up to five amperes. In parallel with the moving coils is an inductive shunt, which permits only a small part of the total current to flow through the moving coil. This current through the moving coil is directly proportional to the total current through the instrument. The shunt has the same ratio of reactance to resistance as has the moving coil, thus the instrument will be reasonably correct at all frequencies with which it is designed to be used.

The meter is mechanically damped by means of aluminum vanes that move in enclosed air chambers. Although electrodynamometer type meters are very accurate, they do not have the sensitivity of the D'Arsonval type meter. For this reason they are not widely used outside the laboratory.

Meter Used for Measuring Resistance

The two instruments most commonly used to check the continuity, or to measure the resistance of a circuit or circuit element, are the OHMMETER and the MEGGER (megohmmeter). The ohmmeter is widely used to measure resistance and check the continuity of electrical circuits and devices. Its range usually extends to only a few megohms. The megger is widely used for measuring insulation resistance, such as between a wire and the outer surface of its insulation, and insulation resistance of cables and insulators. The range of a megger may extend to more than 1,000 megohms.

OHMMETER

The ohmmeter consists of a d-c milliammeter, which was discussed earlier in this chapter, with a few added features. The added features are:

1. A d-c source of potential (usually a three-volt battery).
2. One or more resistors (one of which is variable). A simple ohmmeter circuit is shown in figure 11-12.

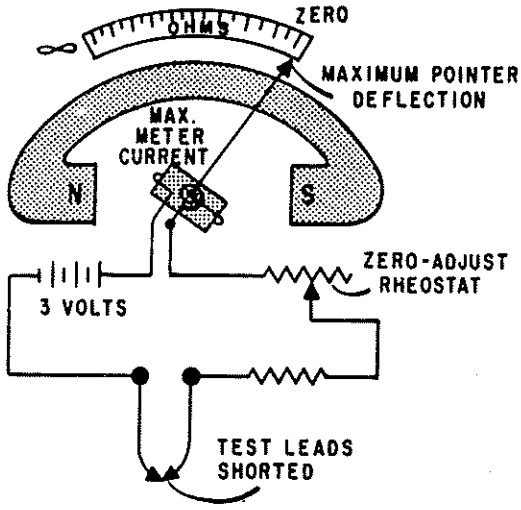


Figure 11-12.—Simple ohmmeter circuit.

The ohmmeter's pointer deflection is controlled by the amount of battery current passing through the moving coil. Before measuring the resistance of an unknown resistor or electrical circuit, the test leads of the ohmmeter are first shorted together, as shown in figure 11-12. With the leads shorted the meter is calibrated for proper operation on the selected range. (While the leads are shorted meter current is maximum and the pointer deflects a maximum amount, somewhere near the zero position on the ohms scale.) When the variable resistor (rheostat) is adjusted properly, with the leads shorted, the pointer of the meter will come to rest exactly on the zero graduation. This indicates ZERO RESISTANCE between the test leads, which in fact are shorted together. The zero readings of series-type ohmmeters are sometimes on the right-hand side of the scale, whereas the zero reading for ammeters and voltmeters is generally to the left-hand side of the scale. When the test leads of an ohmmeter are separated, the pointer of the meter will return to the left side of the scale, due to the interruption of current and the spring tension acting on the movable coil assembly.

After the ohmmeter is adjusted for zero reading, it is ready to be connected in a circuit to measure resistance. A typical circuit and ohmmeter arrangement is shown in figure 11-13.

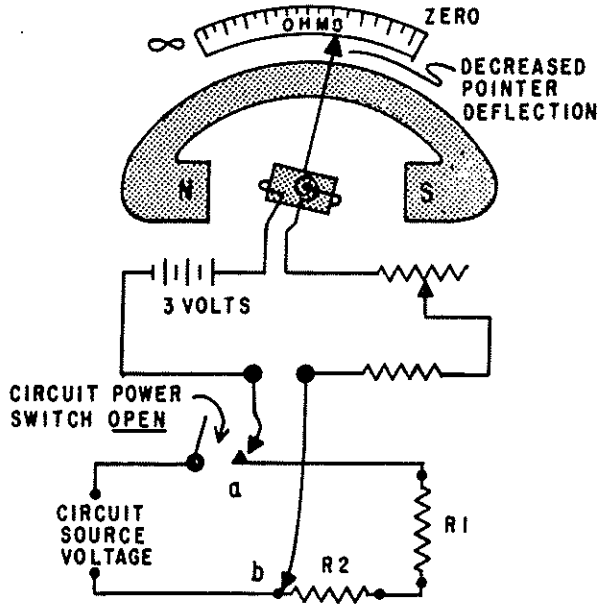


Figure 11-13.—Measuring circuit resistance with an ohmmeter.

The power switch of the circuit to be measured should always be in the OFF position. This

prevents the circuit's source voltage from being applied across the meter, which could cause damage to the meter movement.

The test leads of the ohmmeter are connected across (in series with) the circuit to be measured. (See fig. 11-13.) This causes the current produced by the meter's three-volt battery to flow through the circuit being tested. Assume that the meter test leads are connected at points *a* and *b* of figure 11-13. The amount of current that flows through the meter coil will depend on the resistance of resistors, *R*1 and *R*2, plus the resistance of the meter. Since the meter has been preadjusted (zeroed), the amount of coil movement now depends solely on the resistance of *R*1 and *R*2. The inclusion of *R*1 and *R*2 raised the total series resistance, decreased the current, and thus decreased the pointer deflection. The pointer will now come to rest at a scale figure indicating the combined resistance of *R*1 and *R*2. If *R*1 or *R*2, or both, were replaced with a resistor(s) having a larger ohmic value, the current flow in the moving coil of the meter would be decreased still more. The deflection would also be further decreased, and the scale indication would read a still higher circuit resistance. Movement of the moving coil is proportional to the amount of current flow. The scale reading of the meter, in ohms, is inversely proportional to current flow in the moving coil.

The amount of circuit resistance to be measured may vary over a wide range. In some cases it may be only a few ohms, and in others it may be as great as 1,000,000 ohms. To enable the meter to indicate any value being measured, with the least error, scale multiplication features are incorporated in most ohmmeters. For example, a typical meter will have four test lead jacks, marked as follows—COMMON, *R* x 1, *R* x 10, and *R* x 100. The jack marked COMMON is connected internally through the battery to one side of the moving coil of the ohmmeter. The jacks marked *R* x 1, *R* x 10, and *R* x 100 are connected to three different size resistors located within the ohmmeter. This is shown in figure 11-14.

Some ohmmeters are equipped with a selector switch for selecting the multiplication scale desired, so that only two test lead jacks are necessary. Other meters have a separate jack for each range, as shown in figure 11-14. The range to be used in measuring any particular unknown resistance (R_x in fig. 11-14) depends on the approximate ohmic value of the unknown resistance. For instance, assume the ohmmeter scale in figure 11-14 is calibrated in divisions from zero to 1,000. If R_x is greater than 1,000 ohms, and the *R* x 1 range is being used, the ohmmeter cannot measure it. This occurs because the combined series resistance of resistor *R* x 1 and R_x is too great to allow sufficient battery current to flow to deflect the pointer away from infinity (∞). The test lead would have to be plugged into the next range, *R* x 10. With this done, assume the pointer deflects to indicate 375 ohms. This would indicate that R_x has 375 x 10 = 3,750 ohms resistance. The change of range caused the deflection because resistor *R* x 10 has only 1/10 the resistance of resistor *R* x 1. Thus, selecting the smaller series resistance permitted a battery current of sufficient amount to cause a useful pointer deflection. If the *R* x 100 range were used to measure the same 3,750-ohm resistor, the pointer would deflect still further, to the 37.5 ohm position. This increased deflection would occur because resistor *R* x 100 has only 1/10 the resistance of resistor *R* x 10.

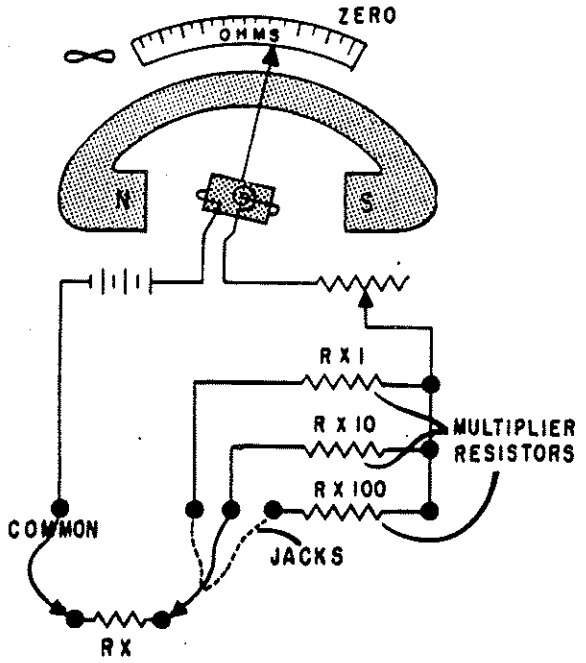


Figure 11-14.—Ohmmeter with multiplication jacks.

The foregoing circuit arrangement allows the same amount of current to flow through the meter's moving coil whether the meter measures 10,000 ohms on the *R* x 1 scale, or 100,000

ohms on the R x 10 scale, or 1,000,000 ohms on the R x 100 scale.

It always takes the same amount of current to deflect the pointer to a certain position on the scale (midscale position for example), regardless of the multiplication factor being used. Since the multiplier resistors are of different values, it is necessary to ALWAYS "zero" adjust the meter for each multiplication factor selected. The operator of the ohmmeter should select the multiplication factor that will result in the pointer coming to rest as near as possible to the midpoint of the scale. This enables the operator to read the resistance more accurately, because the scale readings are more easily interpreted at or near midpoint.

MEGGER

An ordinary ohmmeter cannot be used for measuring resistance of multimillions of ohms, such as conductor insulation. To adequately test for insulation breakdown, it is necessary to use a much higher potential than is furnished by an ohmmeter's battery. This potential is placed between the conductor and the outside surface of the insulation.

An instrument called a MEGGER (megohmmeter) is used for these tests. The megger (fig. 11-15 (A)) is a portable instrument consisting of two primary elements—(1) a hand-driven d-c generator, G, which supplies the necessary voltage for making the measurement, and (2) the instrument portion, which indicates the value of the resistance being measured. The instrument portion is of the opposed-coil type as shown in figure 11-15 (A). Coils a and b are mounted on the movable member c with a fixed angular relationship to each other, and are free to turn as a unit in a magnetic field. Coil b tends to move the pointer counterclockwise, and coil a clockwise.

Coil a is connected in series with $R3$ and the unknown resistance, R_X, to be measured. The combination of coil $R3$, and R_X form a direct series path between the + and - brushes of the d-c generator. Coil b is connected in series with $R2$ and this combination is also connected across the generator. There are no restraining springs on the movable member of the instrument portion of the megger. Therefore, when the generator is not operated, the pointer floats freely and may come to rest at any position on the scale.

The guard ring intercepts leakage current. Any leakage currents intercepted are shunted to the negative side of the generator. They do not flow through coil a; therefore, they do not affect the meter reading.

If the test leads are open-circuited, no current flows in coil a. However, current flows internally through coil b, and deflects the pointer to infinity, which indicates a resistance too large to measure. When a resistance such as R_X is connected between the test leads, current also flows in coil a, tending to move the pointer clockwise. At the same time, coil b still tends to move the pointer counterclockwise. Therefore, the moving element, composed of both coils and the pointer, comes to rest at a position at which the two forces are balanced. This position depends upon the value of the external resistance, which controls the relative magnitude of current in coil a. Because changes in voltage affect both coil a and coil b in the same proportion, the position of the moving system is independent of the voltage. If the test leads are short-circuited, the pointer rests at zero because the current in a is relatively large. The instrument is not injured under the circumstances because the current is limited by $R3$.

The external view of one type of megger is shown in figure 11-15 (B).

Meggers provided aboard ship usually are rated at 500 volts. To avoid excessive test voltages, most meggers are equipped with friction clutches. When the generator is cranked faster than its rated speed, the clutch slips and the generator speed and output voltage are not permitted to exceed their rated values. For extended ranges, a 1,000-volt generator is available. When extremely high resistances—for example, 10,000 megohms or more—are to be measured, a high voltage is needed to cause sufficient current flow to actuate the meter movement.

Multimeter

The MULTIMETER is a multipurpose instrument that can measure resistance, voltage, or current. It contains one milliammeter. The face of the instrument has separate graduated scales

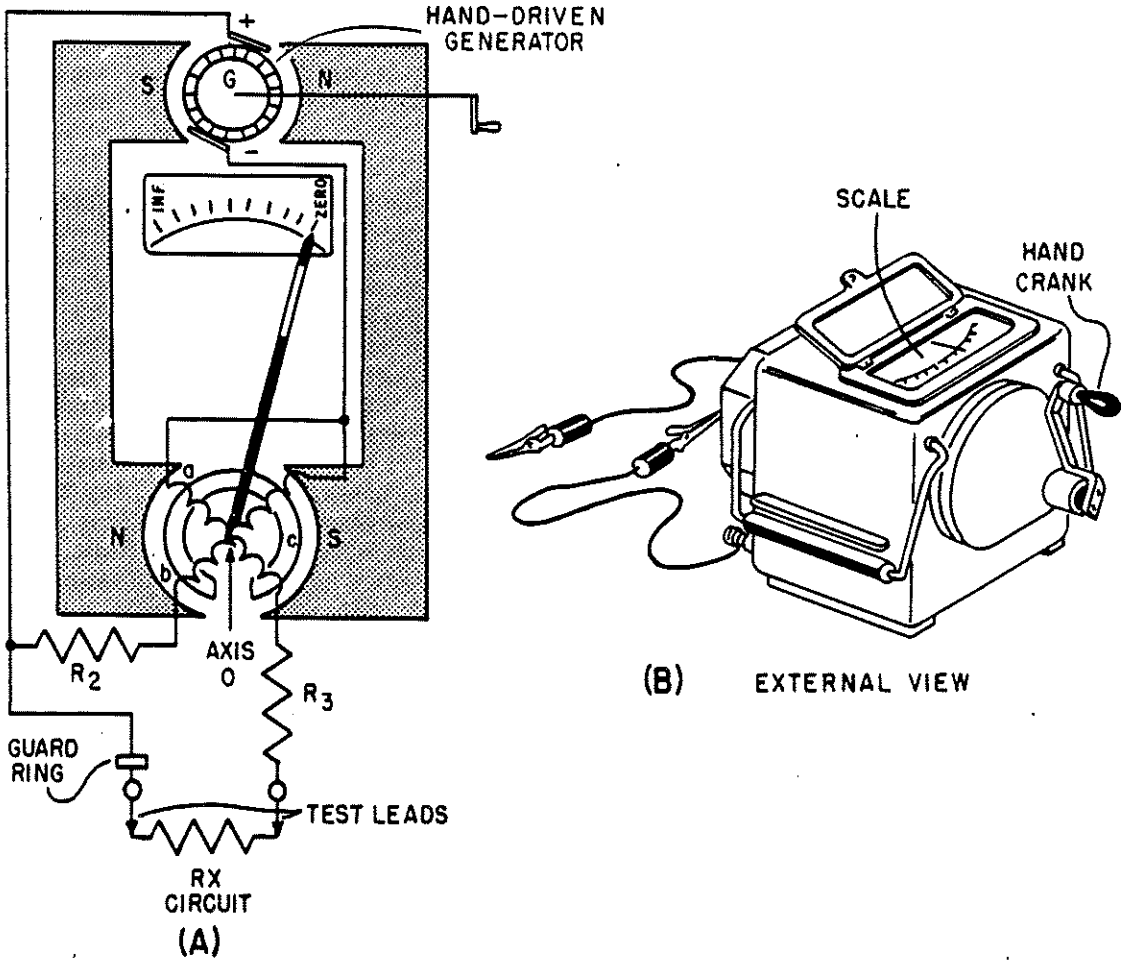


Figure 11-15.—(A) Megger internal circuit; (B) external view of megger.

to indicate the three values that can be measured. Figure 12-16 shows a multimeter that is widely used in the Navy today.

The front panel of the multimeter is constructed and labeled in such a way that all functions are self explanatory. One pin jack marked -DC ±AC OHMS is common to all functions and ranges. One test lead is always plugged into this common jack and the remaining lead into the jack marked for the particular function or range desired. The internal circuit arrangement of the meter is controlled by means of the FUNCTION switch. This switch selects the proper circuit elements for the type of measurement desired. The desired voltage, current or ohmmeter range is determined by the combined action of positioning the function and range switches and selecting certain pin jacks. The range switch selects the resistance or current range and the pin jacks select the voltage range. The function switch selects the type of operation to be performed. Separate pin jacks are provided for ohms and for the 10-ampere range. A CASE GROUND jack is connected directly to the cast aluminum case.

The meter panel contains the following operating controls:

1. FUNCTION SWITCH. This is a six position rotary switch which is clearly marked with the type of measurement to be taken. It is located in the lower left-hand corner of the front panel.

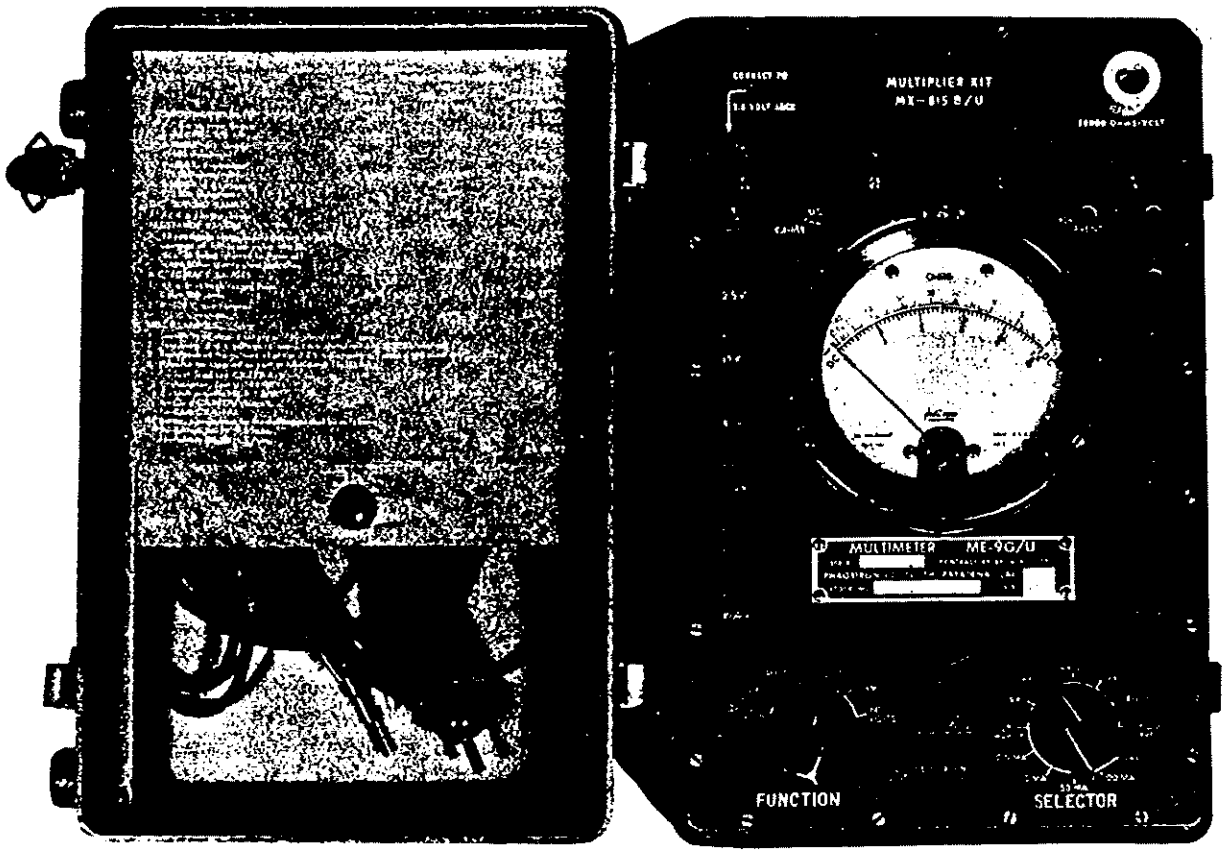


Figure 11-16.—Multimeter.

2. RANGE SWITCH. This is a twelve position switch used in selecting one of five resistance ranges or one of seven current ranges. This switch is located in the lower right-hand corner of the front panel. An additional current range (10 amperes) is brought out to a separate pin jack, because of the magnitude of the current.

3. OHMS ZERO ADJ. This control is a rheostat used to zero the pointer on the ohmmeter. With the test leads shorted the rheostat is turned until the pointer comes to rest at zero. The rheostat also serves to compensate for variations in battery voltage, and is located in the lower center section of the front panel.

The following operational procedures should be used when making measurements with the meter.

1. A-C VOLTS MEASUREMENTS. Turn FUNCTION switch to AC VOLTS. Plug one test lead into the ±AC jack. Plug the other lead into the desired 1,000 OHMS PER VOLT jack.

2. OHMS MEASUREMENTS. Turn FUNCTION switch to OHMS. Plug leads into the two OHMS jacks. Turn the range switch to the desired resistance range. Short the two test leads together and set the indicator pointer to zero ohms (top scale on the indicator) by rotating the OHMS ZERO ADJ.

3. D-C CURRENT MEASUREMENT. Turn FUNCTION switch to DC CURRENT. Plug the black test lead into the -DC jack. For ranges from 250 microamperes to ° 5 amperes full scale, plug the red lead into the jack marked +DC current. Use the jack marked +10 AMPS ONLY for current reading between 2.5 amperes and 10 amperes range.

4. D-C VOLTS MEASUREMENTS at 1,000 OHMS PER VOLT. Turn the FUNCTION switch to 1,000 Ω/VDC. Plug the black lead into the -DC jack. Plug the red lead into the desired range jack.

5. D-C VOLTS MEASUREMENTS at 20,000 OHMS PER VOLT. An indicator reversing position is available on the 20,000 ohms per volt measurements and is selected by indexing the FUNCTION switch to DIRECT or REVERSE.

This permits measurement of voltage, either positive or negative in polarity, while still keeping the instrument case and the common d-c input jack at the same potential as the chassis of the device under check. Accordingly, the following procedure should always be followed when using the 20,000 ohms per volt ranges, particularly where the 1,000 or 5,000 volt ranges are used.

a. Plug the black lead into the -DC jack.

b. Connect the other end of the black lead solidly to the chassis or exposed metal part of the device under check.

c. Turn the FUNCTION switch to "20,000 Ω/VDC DIRECT" if the voltage to be measured is positive with respect to chassis.

d. Turn the FUNCTION switch to REVERSE if the voltage is expected to be negative with respect to chassis.

NOTE: The CASE GROUND jack is connected directly to the metal case. It is not connected to any part of the multimeter circuit. For protection of operating personnel it should be jumpered to an earth or common ground.

Moving Iron-Vane Meter

The moving iron-vane meter is another basic type of meter. Unlike the D'Arsonval-type meter, which employs permanent magnets, the moving iron-vane meter depends on induced magnetism for its operation. It employs the principle of repulsion between two concentric iron vanes, one fixed and one movable, placed inside a coil, as shown in figure 11-17 (A). A pointer is attached to the movable vane.

When current flows through the coil, the two iron vanes become magnetized with north poles at their upper ends and south poles at their lower ends for one direction of current through the coil, as shown in the figure. Because like poles repel, the unbalanced component of force tangent to the movable element causes it to turn against the force exerted by the springs.

The movable vane is rectangular in shape, and the fixed vane is tapered. This design permits the use of a relatively uniform scale.

When no current flows through the coil, the movable vane is positioned so that it is opposite the larger portion of the tapered fixed vane, and the scale reading is zero. The amount of magnetization of the vanes depends on the strength of the field, which in turn, depends on the amount of current flowing through the coil. The force of repulsion is greater opposite the larger end of the fixed vane than it is nearer the smaller end. Therefore, the movable vane moves toward the smaller end through an angle that is proportional to the magnitude of the coil current. The movement ceases when the force of repulsion is balanced by the restoring force of the spring.

Because the repulsion is always in the same direction (toward the smaller end of the fixed vane) regardless of the direction of current flow through the coil, the moving iron-vane instrument operates on either d-c or a-c circuits.

Mechanical damping in this type of instrument is obtained by the use of an aluminum vane attached to the shaft (not shown in the figure) in such a way that, as the shaft moves, the vane moves in a restricted air space.

When the moving iron-vane meter is designed to be used as an ammeter, the coil is wound with relatively few turns of large wire in order to carry the rated current.

When the moving iron-vane meter is designed to be used as a voltmeter the solenoid is wound with many turns of small wire. Portable voltmeters are made with self-contained series resistance for ranges up to 750 volts. Higher ranges are obtained by the use of additional external multipliers. An external view of a moving iron-vane meter is shown in figure 11-17 (B).

The moving iron-vane instrument may be used to measure direct current, but has an error due to residual magnetism in the vanes. The error may be minimized by reversing the meter connections and averaging the readings. When used on a-c circuits the instrument has an accuracy of 0.5 percent. Because of its simplicity, its relatively low cost, and the fact that no current is conducted to the moving element; this type of movement is used extensively to measure current and voltage in a-c power circuits.

However, because the reluctance of the magnetic circuit is high, the moving iron-vane meter requires much more power to produce full-scale deflection than is required by a D'Arsonval meter of the same range. Therefore, the moving iron-vane meter is seldom used in high-resistance low-power circuits.

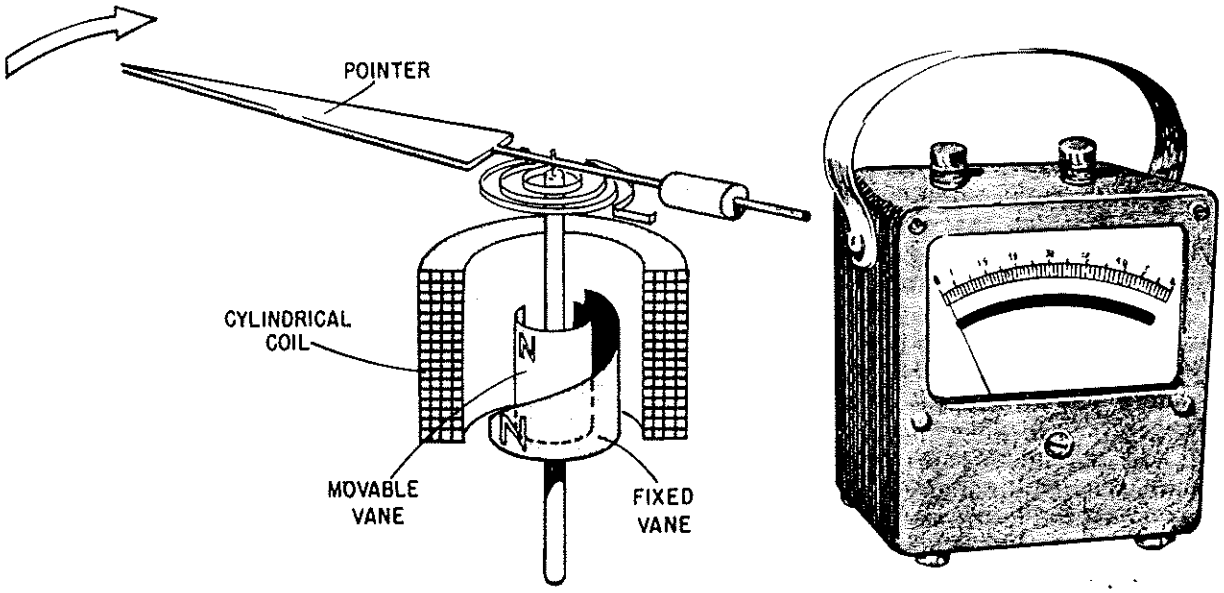


Figure 11-17.–(A) Simplified diagram of a moving iron-vane meter, (B) external view.

Inclined-Coil Iron-Vane Meter

The principle of the moving iron-vane mechanism is applied to the inclined-coil type of meter shown in figure 11-18. The inclined-coil iron-vane meter has a coil mounted at an angle to the shaft. Attached obliquely to the shaft, and located inside the coil, are two soft-iron vanes. When no current flows through the coil, a control spring holds the pointer at zero and the iron vanes lie in planes parallel to the plane of the coil. When current flows through the coil, the vanes tend to line up with magnetic lines passing through the center of the coil at right angles to the plane of the coil. Thus the vanes rotate against the spring action to move the pointer over the scale.

The iron vanes tend to line up with the magnetic lines regardless of the direction of current flow through the coil. Therefore, the inclined-coil iron-vane meter can be used to measure either alternating current or direct current. The aluminum disk and the drag magnets provide electromagnetic damping.

Like the moving iron-vane meter, the inclined-coil type requires a relatively large amount of current for full-scale deflection and hence is seldom used in high-resistance low-power circuits.

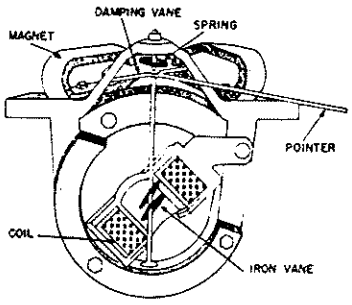


Figure 11-18.–Inclined-coil iron-vane meter.

As in the moving iron-vane instrument, the inclined-coil instrument is wound with few turns of relatively large wire when used as an ammeter and with many turns of small wire when used as a voltmeter.

Thermocouple-Type Meter

If two of the ends of two dissimilar metals are welded together and this junction is heated, a d-c voltage is developed across the two open ends. The voltage developed depends on the material of which the wires are made and on the difference in temperature between the heated junction and the open ends.

In one type of instrument, the junction is heated electrically by the flow of current through a heater element. It does not matter whether the current is alternating or direct because the heating effect is independent of current direction. The maximum current that may be measured depends on the current rating of the heater, the heat that the thermocouple can stand without being damaged, and on the current rating of the meter used with the thermocouple. Voltage may also be measured if a suitable resistor is placed in series with the heater.

A simplified schematic diagram of one type of thermocouple is shown in figure 11-19. The input current flows through the heater strip via the terminal blocks. The function of the heater strip is to heat the thermocouple, which is composed of a junction of two dissimilar wires welded to the heater strip. The open ends of these wires are connected to the center of two copper compensating strips. The function of these strips is to radiate heat so that the open ends of the wires will be much cooler than the junction end of the wires; thus permitting a higher voltage to be developed across the open ends of the thermocouple. The compensating strips are thermally and electrically insulated from the terminal blocks.

The heat produced by the flow of line current through the heater strip is proportional to the square of the heating current ($P = I^2R$). Because the voltage appearing across the two open terminals is proportional to the temperature, the movement of the meter element connected across these terminals is proportional to the square of the current flowing through the heater element. The scale of the meter is crowded near the zero end, and is progressively less

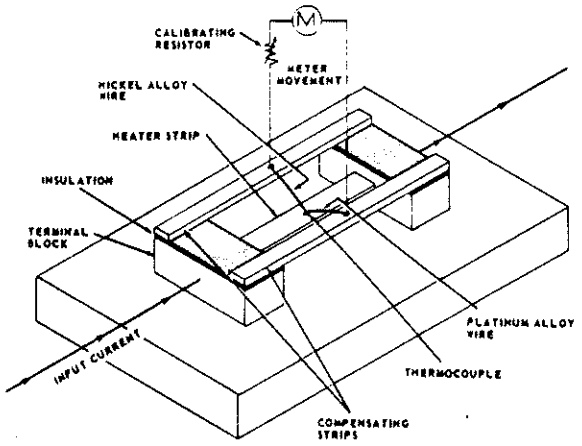


Figure 11-19.—Simplified schematic of one type of thermocouple.

crowded near the maximum end of the scale. Because the lower portion of the scale is crowded the reading is necessarily less accurate. For the sake of accuracy in making a given measurement, it is desirable to choose a meter in which the deflection will extend at least to the more open portion of the scale.

The meter used with the thermocouple should have low resistance to match the low resistance of the thermocouple, and it must deflect full scale when rated current flows through the heater. Because the resistance must be low and the sensitivity high, the moving element must be light.

A more nearly uniform meter scale may be obtained if the permanent magnet of the meter is constructed so that as the coil rotates (needle moves up scale), it moves into a magnetic field of less and less density. The torque then increases approximately as the first power of the current instead of as the square of the current, and a more linear scale is achieved.

If the thermocouple is burned out by excessive current through the heater strip, it may be replaced and the meter recalibrated by means of the calibrating variable resistor.

QUIZ

1. In a D'Arsonval type meter, the primary purpose of the iron core is to
   a. dampen coil movement
   b. concentrate the flux between the core and the pole piece
   c. concentrate the flux between the core and the hairsprings
   d. weaken the flux between the core and the pole piece
2. The D'Arsonval movement operates on the principle of
   a. mutual induction
   b. repulsion
   c. magnetic repulsion and attraction
   d. magnetic attraction
3. In order to measure large currents with the D'Arsonval ammeter,
   a. the meter must be made more rugged
   b. an increased number of turns must be put on the moving coil
   c. shunts are used
   d. the pointer must be lengthened
4. The primary purpose of the megger is to measure
   a. milliohms
   b. kilohms
   c. megohms
   d. microhms
5. A moving iron-vane meter works on the principle of
   a. induction
   b. repulsion
   c. conduction
   d. attraction
6. When hairsprings are used in a D'Arsonval type meter, they
   a. serve as conductors
   b. are wound oppositely and provide restoring forces
   c. are attached to the ends of the bobbin
   d. all of the above are true
7. The metal ribbons attached to the moving coil in the galvanometer have no force on them when the
   a. north pole of the moving coil is close to the south pole of the horseshoe magnet
   b. north pole of the moving coil is as close as possible to the north pole of the horseshoe magnet
   c. north pole of the moving coil is 90° from the north pole of the horseshoe magnet
   d. none of the above
8. When shunts are used with an ammeter they
   a. must be located within the case
   b. must be located outside the case
   c. may be located either inside or outside the case
   d. reduce the accuracy of the movement
9. The power supply for a megger comes from
   a. two flashlight batteries
   b. a hand-driven generator
   c. any 115 v. wall plug
   d. the aircraft battery
10. The iron-vane meter can be used on
    a. a.c. only
    b. a.c. and d.c.
    c. d.c. only
    d. rectified a.c.
11. The Weston meter uses the principle of operation of the
    a. D'Arsonval galvanometer
    b. Thompson incline coil
    c. iron vane
    d. V. T. V. M.
12. Current-measuring instruments must always be connected in
    a. parallel with a circuit
    b. series with a circuit
    c. series-parallel with a circuit
    d. delta with the shunt
13. If the pointer fails to come back to zero when the megger is not in use,
    a. the megger is out of calibration
    b. this is normal operation
    c. the hairsprings are burned out
    d. the pointer is stuck
14. When using ammeters,
    a. reverse polarity must be used
    b. + or - polarity can be used
    c. polarity should be observed
    d. regardless of polarity, the instrument cannot be damaged because it is grounded
15. For measuring resistances of multimillions of ohms, use a/an
    a. TS 297 multimeter
    b. ohmmeter with high scales
    c. megger
    d. combustion volt ammeter
16. Dampening is accomplished in the iron-vane meter by
    a. hairsprings
    b. the hermetically sealed case
    c. an aluminum bobbin
    d. an aluminum vane
17. Balance springs on each end of the shaft of the Weston ammeter
    a. are used to carry current to the moving coil
    b. are not balanced due to temperature change
    c. provide a turning force for the pointer
    d. are factory adjusted and must not be readjusted

18. The electrodynamometer-type meter employs
    a. two permanent magnets
    b. one permanent magnet and one electromagnet
    c. two fixed coils and one movable permanent magnet
    d. none of the above
19. With the ohmmeter setting on R x 1, it takes 0.01 ma. to deflect the pointer to half scale. If the meter was set on R x 100, how much would it take to deflect the pointer to half scale?
    a. 0.1 ma.
    b. 0.01 ma.
    c. 0.001 ma.
    d. 1.0 ma.
20. Electrodynamometer-type meters
    a. never utilize shunts
    b. utilize four coils, all of which are movable
    c. are seldom used in the laboratory because they are not accurate enough
    d. are not as sensitive as the D'Arsonval meter
21. Meggers provided aboard ships are usually rated at
    a. 250 volts
    b. 500 volts
    c. 750 volts
    d. 1,000 volts
22. The voltage developed in the thermocouple-type meter depends on the
    a. material of which the wires are made
    b. direction of current flow
    c. frequency of the heater voltage
    d. the type of meter movement
23. A multimeter contains a
    a. voltmeter and wattmeter
    b. voltmeter and frequency meter
    c. voltmeter, ohmmeter, and milliammeter
    d. voltmeter, ammeter, and ohmmeter